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The Proceedings

OF

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MR 56 H	5·3	5·6	6·0	28	50	0·6	10	35
MR 62 H	5·8	6·2	6·6	10	30	0·4	10	33
MR 68 H	6·4	6·8	7·2	3·7	15	0·85	10	29
MR 75 H	7·1	7·5	7·9	4·0	15	1·25	10	27
MR 82 H	7·7	8·2	8·7	5·5	20	1·5	10	25
MR 91 H	8·6	9·1	9·6	8·0	20	2·0	10	23
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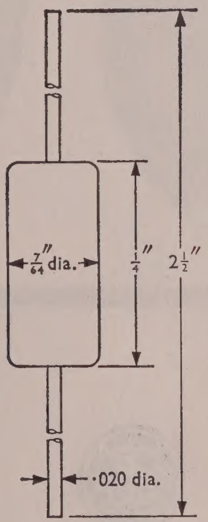

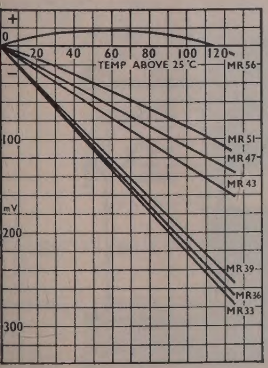

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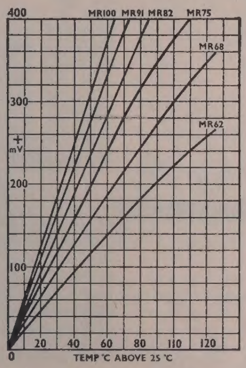

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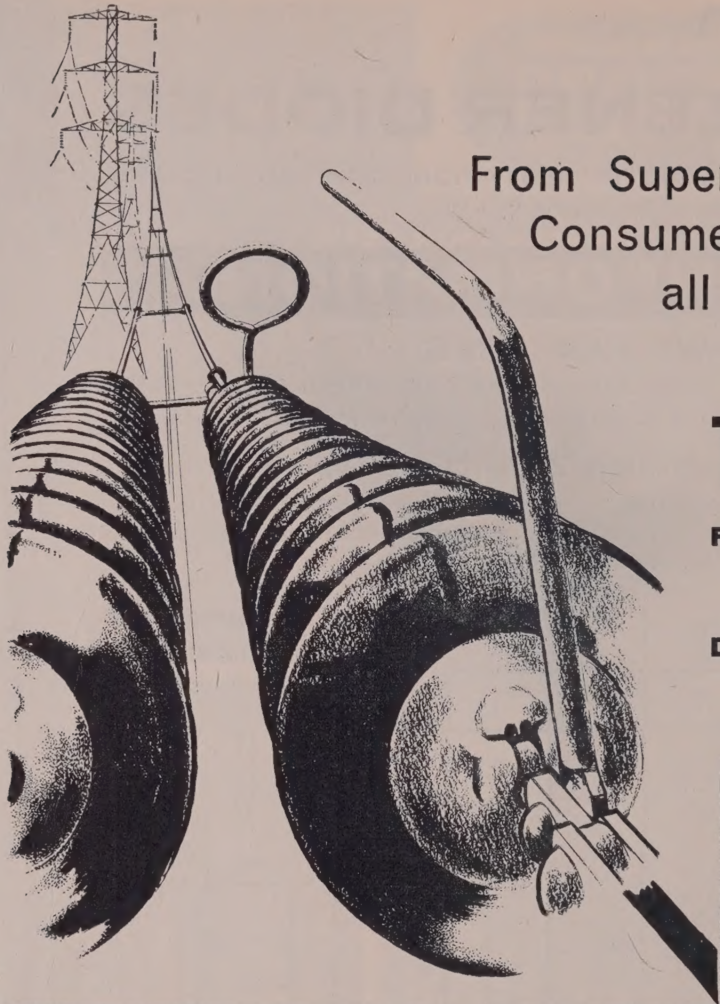

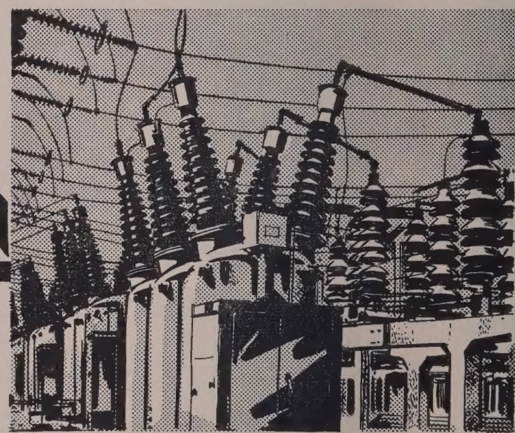

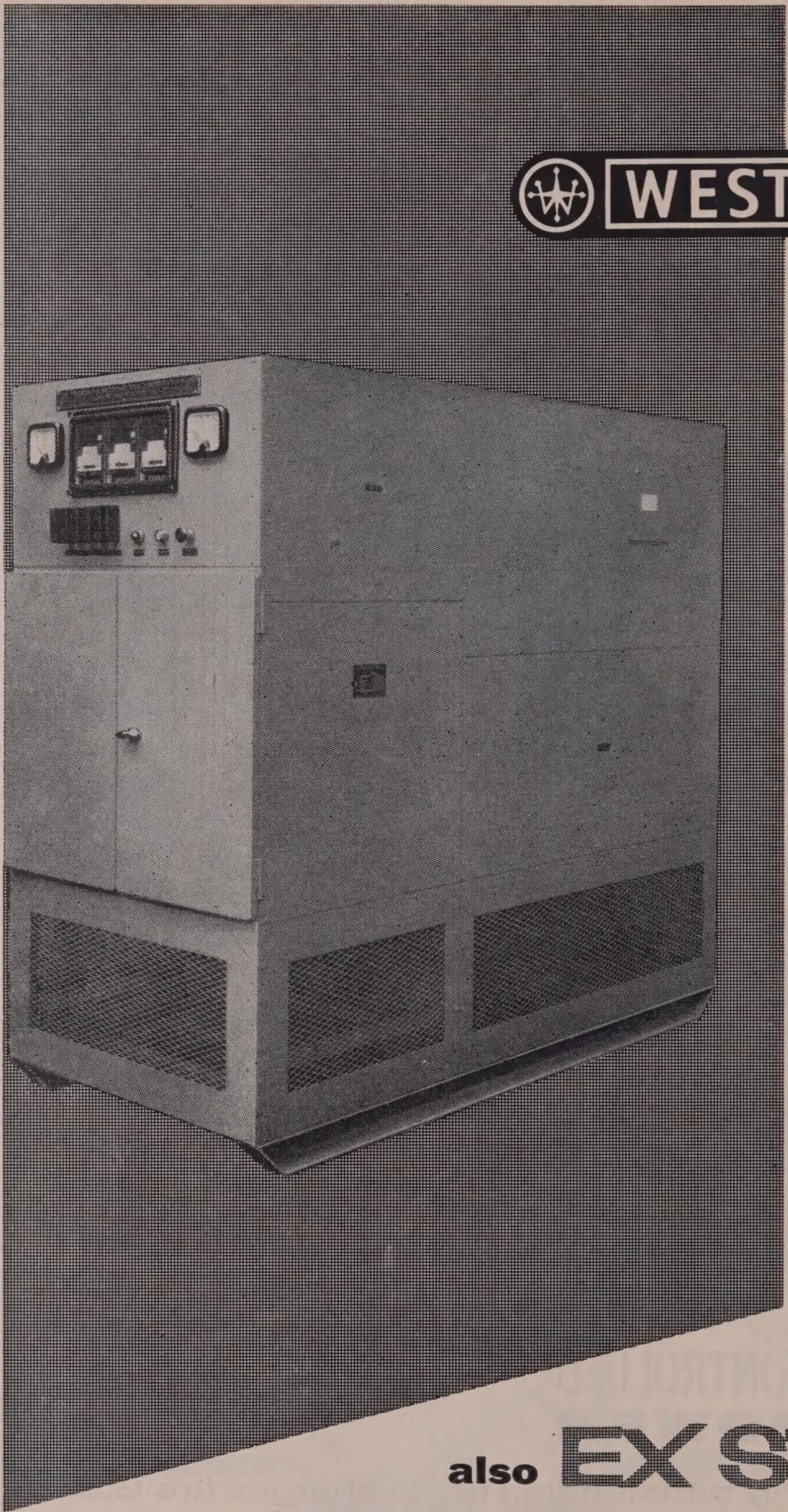

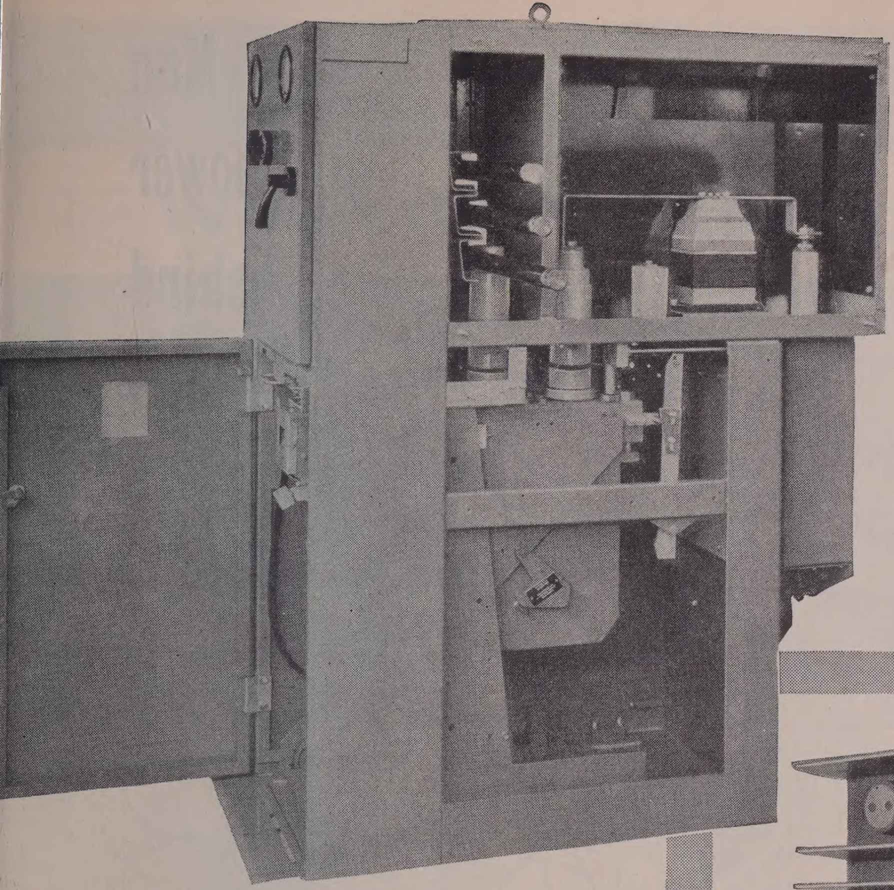

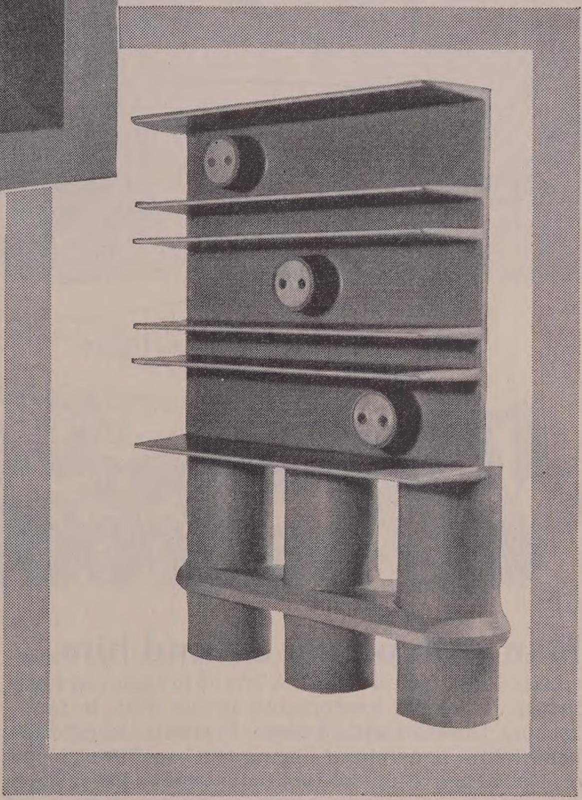


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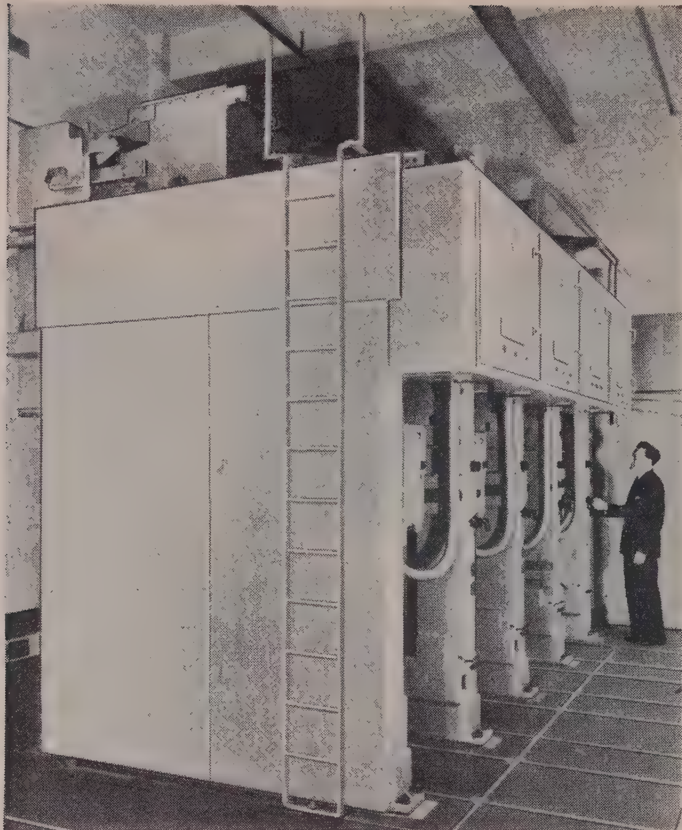

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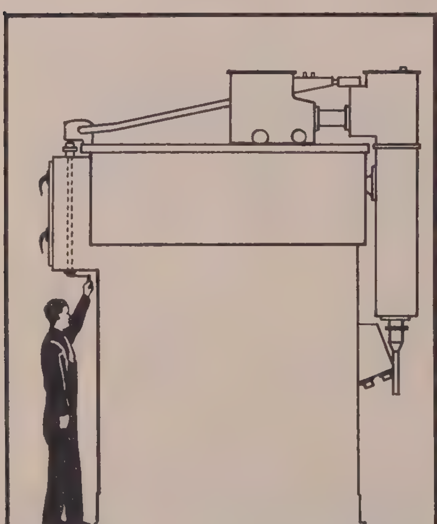

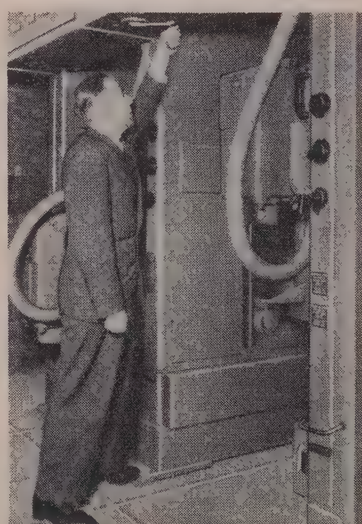

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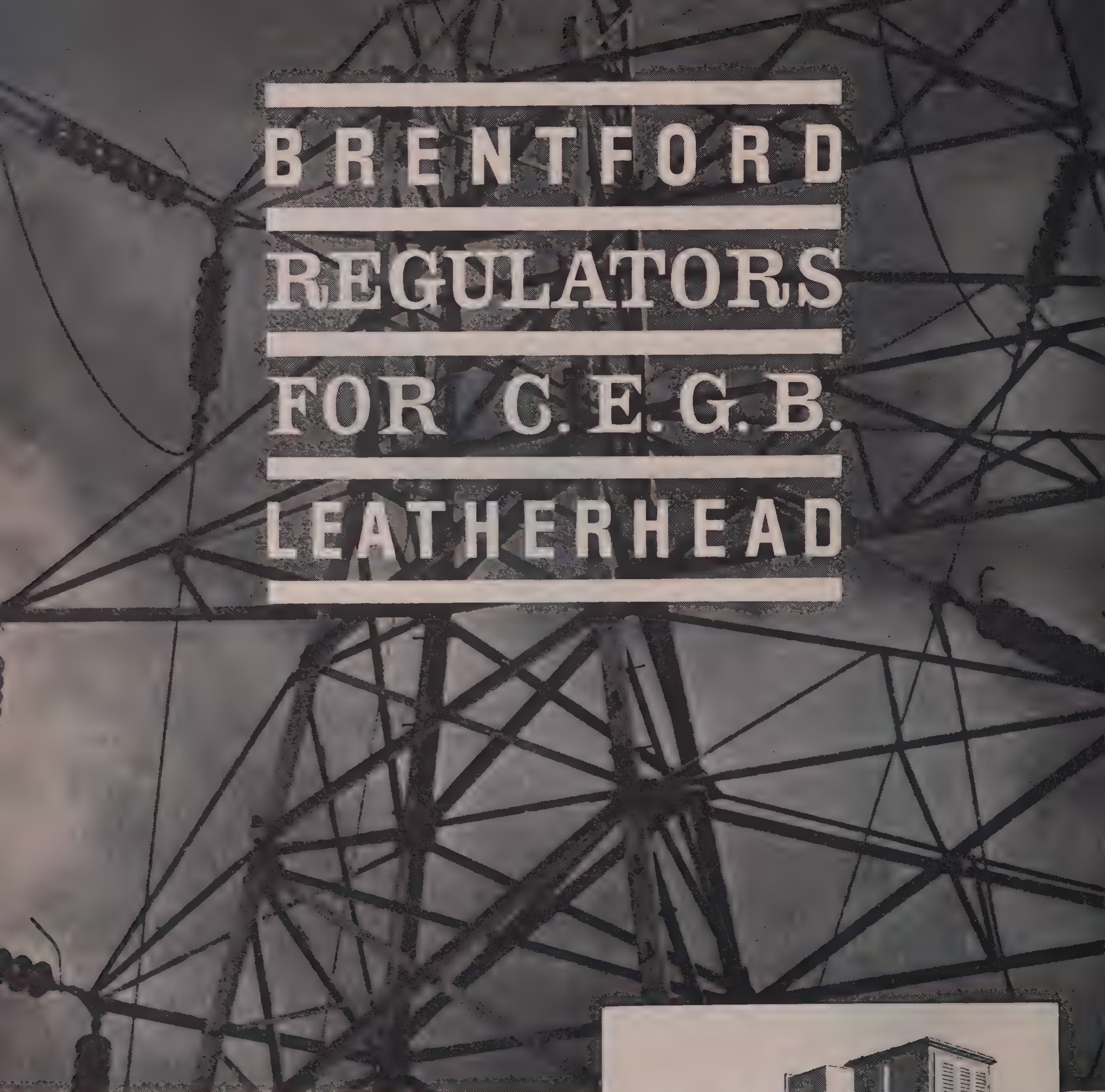
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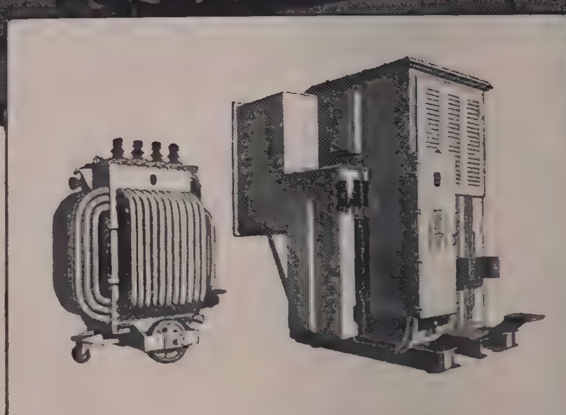

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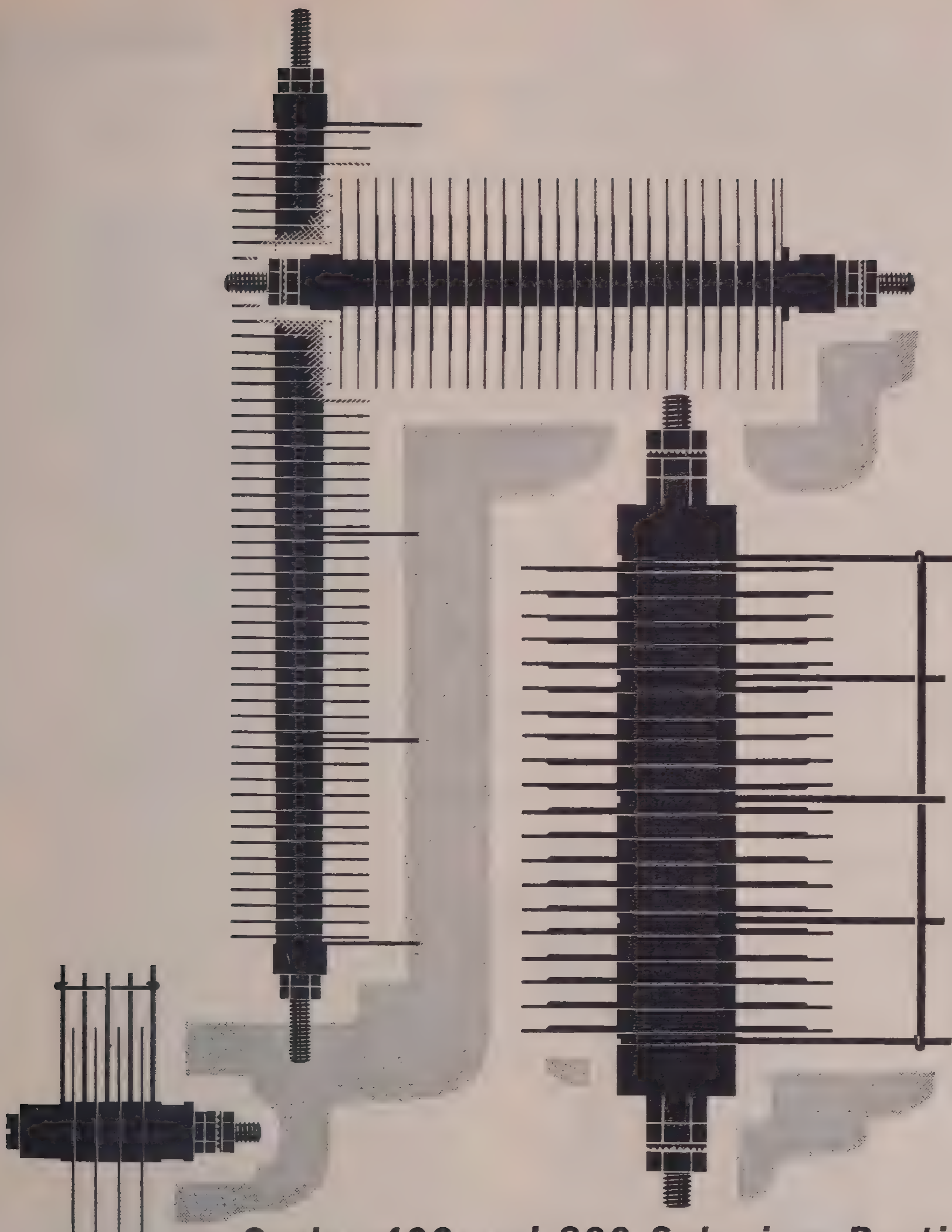

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PROGRESS IN OIL-FILLED CABLES AND THEIR ACCESSORIES

By A. N. ARMAN, Ph.D., and F. J. MIRANDA, Dr.Ing., Members, and G. R. BISHOP.

(The paper was first received 23rd October, 1959, and in revised form 14th November, 1960. It was published in March, 1961, and was read before the SOUTHERN CENTRE 17th April, and the SUPPLY SECTION 19th April, 1961.)

SUMMARY

After recalling the genesis and growth of the oil-filled cable system of power transmission, and touching upon its reliability as proved by 30 years of service experience, the paper dwells in more detail on recent developments. Improvements in insulating and screening materials and in manufacturing techniques, especially that of precision lapping have warranted higher design stresses. The resulting increased consistency of performance has justified closer design limits. The importance is emphasized of balanced development of both a.c. and impulse performance of high-voltage cable and accessories.

Significant reductions in dimensions of oil-filled cable accessories have been effected without reduction in performance level, and the introduction of epoxy-resin castings has permitted a new approach to the design of certain of these accessories.

A development of considerable moment is the increase in permissible operating temperatures, which gives oil-filled cable systems overload capacity commensurate with that of the transformers with which they are frequently associated. Long-term investigations have shown that, with suitable materials and laying conditions, operation for very long periods at conductor temperatures up to 110° C is permissible.

(1) HISTORICAL NOTE

The limitations of conventional 'solid' type cable for use at high voltage, due to ionization of voids, are well known to both cable makers and users. The search for ways of overcoming these limitations has resulted in several types of cable in which ionization is suppressed either (*a*) by preventing formation of voids or (*b*) by tolerating their presence and subjecting them to gas pressure.

The earliest solution, which is in the first category and the first to be put into commercial use, was due to Emanueli, who, as early as 1917, had taken out patents for his oil-filled cable. The first experimental installation was made in 1924, when a 130 kV cable was put into commission at Brugherio near Milan. Its success led to the installation in 1927 of some 18 miles of single-core 600 000 circular mils 132 kV oil-filled cable in New York and Chicago. These cables have given perfect service without a single electrical failure since their installation.

The authors are with Pirelli-General Cable Works, Ltd.

Although initially not as spectacular, the starting-point being a small 66 kV route at Skernside, Co. Durham, in 1929, the use of oil-filled cable in Great Britain rapidly expanded, and by 1931 the first 132 kV systems were commissioned.

By 1936 substantial reductions in dielectric power factor of oil-filled cables, especially in the upper temperature ranges, and improvements in the stability of the impregnating oil, enabled installations of some 35 miles of 220 kV cable in Paris to be contemplated with equanimity, the most important medium in effecting the first-mentioned improvement being the use of water-washed paper. Simultaneously 3-core construction with interstitial ducts was developed in this country, and by the beginning of the Second World War, was being supplied for both 33 and 66 kV systems.

The record of reliable performance in service of oil-filled cables and their accessories is almost unrivalled for high-voltage electrical apparatus. The only case the authors have on record of an interruption of service under normal conditions due to electrical failure of an oil-filled cable occurred in 1949 on a 132 kV cable system. Examination revealed that tearing of insulating papers had occurred, and an intensive investigation showed it to be due to inadequate control during the paper lapping process. As a result, a technique was developed for the application of insulating papers under precisely specified and controlled tensions. The results of this study are fully reported elsewhere.[1]

The only other failures the authors have on record have been one due to a direct lightning stroke on an overhead line directly connected to the cable, another due to a badly made joint and a few due to loss of oil in some installations which in general did not include a low-oil-pressure alarm system. Most of the latter troubles were caused by the enforced use after the Second World War of lead sheathing alloys which cracked under the conditions of slow creep that are sometimes encountered.

Considered conjointly with the many hundreds of miles of oil-filled cable in use (see Appendix 10.1), the almost complete absence of electrical failures is a remarkable tribute to the oil-filled-cable principle. It speaks well for the ability of the original inventors that the oil-filled cable is still the most used

for high-voltage applications and that it is fairly generally accepted as probably the only type now known which can be used for the very high voltages (300 kV and over) for which cable are now required.

In recent years investigations have been proceeding to assess the present condition of the insulation of cables which have been in service for many years. The results, which will be published elsewhere,[2] show very satisfactory stability.

(2) DEVELOPMENTS IN RECENT YEARS

Considerable advances have been made in recent years in the quality of oil-filled cables. These advances are due to improvements in insulating and screening materials, to an understanding of the mechanical stresses resulting from the lapping operation and the subsequent bending and processing of the cable, and finally to improvements in manufacturing and processing equipment.

The most important of these improvements will now be described in some detail.

(2.1) Insulating Materials

(2.1.1) Paper.

The early introduction of 'water-washed' paper has already been mentioned. This resulted in a considerable reduction in dielectric losses. Efforts have since been concentrated in a search for insulating paper, which, whilst retaining good mechanical characteristics, has enhanced electric strength. The relative importance of paper thickness, impermeability and density has been discussed elsewhere,[3,4,5] as well as the importance of macro-uniformity of texture.[6] The scale of improvement in impulse strength which has been obtained is shown by the plane capacitor test results illustrated in Fig. 1. The

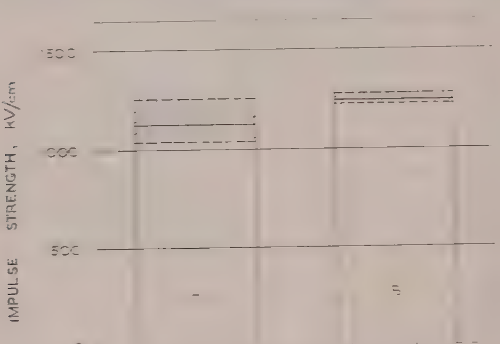

Fig. 1.—Impulse strength of different papers.

A. Paper 3·5 mils thick.
Impermeability: 2 × [illegible] Emanueli units.
Density: [illegible] (65% relative humidity).
B. Paper 3 mils thick.
Impermeability: 6 × [illegible] Emanueli units.
Density: 0·82 (65% relative humidity).

capacitor cable models were approximately 40 mils in thickness and were constructed as described by Gazzana-Priaroggia and Palandri.[5]

It is well known that very thin paper near the conductor gives potentially a great improvement in impulse strength. However, the proper application of thin papers to cables presents considerable technological difficulties. A compromise is therefore necessary, and the modern tendency is to concentrate on paper thicknesses in the range 2–3 mils and to use as high an impermeability as is compatible with the impregnation method used.

(2.1.2) Oil.

It will be of value to review the properties which are required in an oil for the impregnation of oil-filled cables, although these are now well recognized. They may be summarized as follows.

(*a*) The viscosity should be as low as possible compatible with acceptable volatility. Low viscosity makes possible the design of systems for use at very low temperatures. It also reduces the tendency towards low- and high-pressure transient conditions, thus permitting economy in the design of systems.

At the same time the volatility of the oil must be sufficiently low to permit degasification under high vacuum and to avoid excessive flammability. Occasions arise, however, when jointing is best effected by freezing techniques. It may then be advantageous to use an oil of medium viscosity.

(*b*) The oil must be capable of absorbing any residual gas which may remain in the dielectric after installation.

(*c*) The dielectric power factor must be as low as possible, with good chemical stability up to the highest operating temperatures.

The oils in use, refined from naphthenic crudes, represent a compromise between a highly refined oil which would have a very low power factor but would not meet condition (*b*) above and an oil containing a high proportion of aromatic hydrocarbons, which would have a good capacity for gas absorption but would be unstable in respect of power factor.

Since 1951, when a specially low-viscosity oil was introduced, there has been no change in the oils used, but they have been under close study in regard to their behaviour under conditions of increased severity. Characteristics of two typical oils at present in use in this country are given below. Elsewhere, oils having intermediate viscosities are widely used.

		Medium-viscosity grade	*Low-viscosity grade*
Specific gravity	15° C	0·893	0·879
Viscosity, centistokes	20° C	30	14
Viscosity, centistokes	40° C	10	7·5
Aniline number		74	70
Power factor	85° C	0·001	0·001
	100° C	0·002	0·002
	120° C	0·005	0·005

Probably the most informative single test on an oil-filled cable oil is the test for gas absorption under electrical discharge. The test is carried out on a laboratory apparatus which enables the oil, saturated with hydrogen and in contact with hydrogen in a glass tube, to be subjected to electric stress. Changes in gas volume, denoting either absorption or evolution of gas by the oil, are measured in a graduated portion of the apparatus. The behaviour of two different oils with regard to gas absorption is shown in Fig. 2. It will be seen that, whilst their absorption properties are similar in the temperature range of normal cable operation, they differ considerably at higher temperatures.

(2.2) Materials for Electrostatic Screens

(2.2.1) Carbon Paper.

In cables of advanced design operating at high stresses, usually 90–100 kV/cm and above, the conductor is screened with a semiconducting paper obtained by the addition of carbon black uniformly dispersed in the paper pulp during manufacture.

It has been established[3] that, provided that a suitable quality of carbon paper is used, the ionization starting stress of an oil gap in contact with it is appreciably higher than the value obtainable when the same oil gap is in contact with a metallic electrode. Thus a carbon paper screen on the conductor has the advantage of increasing the a.c. breakdown strength of a cable over and above the value which would be obtained with a simple metallic electrostatic screen. Carbon paper also has the property of improving the ageing characteristics of the insulation.[2]

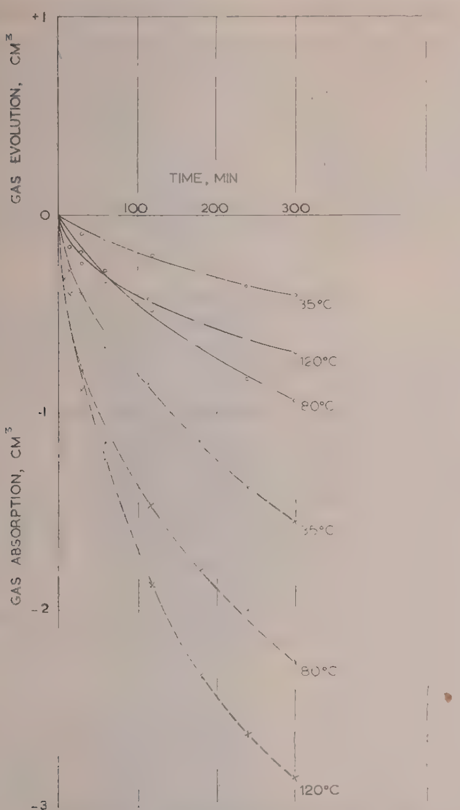

Fig. 2.—Behaviour of different oils in gas absorption test.

—— Oil No. 1.
---- Oil No. 2.

Early types of carbon paper caused an appreciable increase in ower-factor difference, but improved paper-making technique as reduced this effect to comparatively small proportions. A ery recent development in this field is the carbon-insulated aper.[8] In this paper one ply contains carbon black and the cond ply is of normal insulating quality. This paper is applied ith the insulating side facing the dielectric and can be used in vo layers, for instance in the manner shown in Fig. 3. The

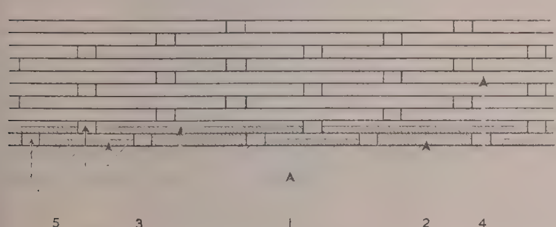

Fig. 3.—Method of application of 2-ply carbon-insulated paper.

1. Conductors.
2. Carbon paper.
3. 2-ply carbon-insulated paper.
4. Insulating paper.
5. Oil gaps.

sults of comparative tests made on capacitor models using ain carbon paper of improved quality and a 2-ply carbon-sulated paper are shown in Fig. 4.

As already noted, a carbon paper screen inevitably causes me increase in power factor. With very-high-voltage cables,

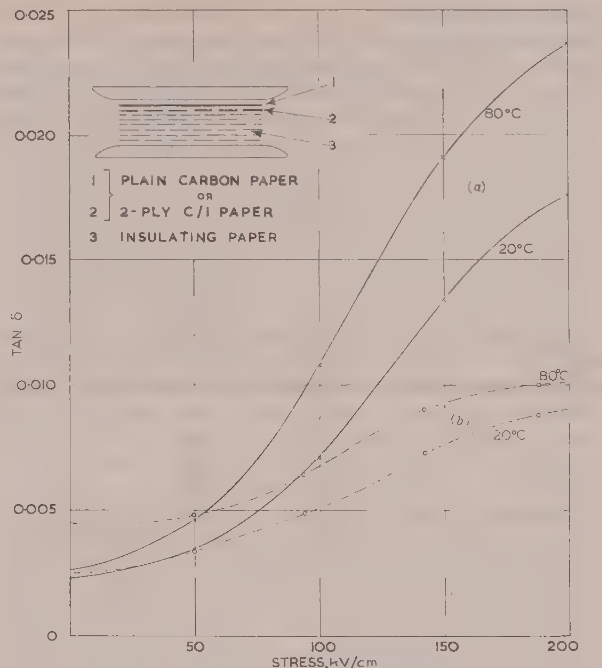

Fig. 4.—Comparative power-factor tests on capacitor models using plain carbon paper and 2-ply carbon-insulated paper.

(a) —— Plain carbon paper.
(b) ---- 2-ply carbon-insulated paper.

say 132 kV and above, the power factor at working voltage is hardly affected, but it increases with the test voltage. It is customary during routine tests to measure the power factor at working voltage (base value) and at twice working voltage and to take the power-factor difference as a measure of quality of the processing of the cable. It is clear that this assessment should take into account whether or not a carbon paper screen is used. This is now recognized by a number of authorities, but it is not yet generally appreciated.

With low-voltage cables such as 33 kV, the base value as well as the power-factor difference can be affected, and although reductions can be obtained for instance with 2-ply carbon-insulated paper, the increase in power factor and especially in power-factor difference can be appreciable. Values obtained on an experimental 33 kV cable compared with a cable of normal design are as follows:

	Base value	*Power-factor difference*
Conductor unscreened (standard cable)	0·0025	0·0005
Conductor screened with carbon-insulated paper	0·0029	0·0015

Further work in progress shows that an improvement on these figures is to be expected.

If full advantage is to be taken of the increased impulse strength obtainable with the newly-developed insulating papers, it is highly desirable to increase the a.c. strength also by a comparable proportion. As already stated, this latter increase is readily obtained with carbon-paper conductor screening. It follows that the time is fast approaching when this type of screen will be used also at the lower voltages. In such instances it may be necessary to increase somewhat the acceptable limits of base value and especially of power-factor difference and to accept these increases as an inherent characteristic of cables so constructed.

(2.2.2) **Metallized Paper.**

Metallized paper is used as the outer electrostatic screen, interleaved with either insulating or carbon paper, depending on the screen gradient. It consists of a thin aluminium foil glued on to a paper backing. The mechanical characteristics of this combination are determined by the base paper and thus are similar to those of the insulating papers. This ensures regularity of the interleaved layer on the finished cable.

To permit rapid processing of the cables the metallized paper is perforated. In the past, perforations were obtained by pricking, but this process gave rise to burrs and minute local displacements of the aluminium foil; these localized defects were found to be dangerous when screen stresses were increased.

A great improvement was obtained with punched perforations which have only minor burrs, similar to those present at the edges of the metallized tapes. The stress concentration at these points can still be dangerous when screen stresses are exceptionally high. In such cases adequate measures are taken to reduce their effect. In this respect a combination of carbon and metallized papers has proved successful.

The adhesive used in the manufacture of metallized paper must be selected with care. An adhesive with high dielectric losses will noticeably increase the power factor of a cable if its capacitance per unit length is sufficiently high. Recent improvements in the quality of adhesives are illustrated by the following test results.

The power factor of base paper and adhesive was measured on the dry metallized paper in air at 100° C and at 200 volts. Typical values obtained on early types were of the order of 0·035. With improved adhesives the power factor has been reduced to 0·007 or less.

(2.3) Techniques

(2.3.1) **Lapping.**

Until the late 1940s it had been noted that the breakdown strength of a cable insulation was reduced as the diameter of the conductor was increased. This fact led a number of authorities to the conclusion that there is an inherent correlation between conductor diameter and electric strength. A systematic examination of breakdown paths showed this view to be mistaken. It was observed that creases in the insulation, and especially those close to the conductor, were primarily responsible for low breakdown strength. As these creases occur more readily and are more serious with larger conductors, the true cause of correlation was established.

This led to a mathematical study of the nature and distribution of mechanical pressures exerted on the insulation during lapping and the subsequent bending and processing of the cable, and eventually to the establishment of a fully-controlled lapping technique.[1] No advance could have been made, however, without the parallel development of precision lapping equipment capable of maintaining to within narrow limits the design values of lapping tensions and of registration between layers. A complementary requirement for the same purpose is the control of water content of the paper—a condition which is met by enclosing the lapping machines, together with the store of pads of cut paper, in a humidity-controlled room.

To indicate the scale of improvement due to controlled lapping we have plotted in Fig. 5 the stresses at impulse breakdown progressively obtained from a series of development tests on 100 kV/cm 3 × 0·5 in^2 132 kV cables, immediately before and immediately after the installation of the above-mentioned equipment. The insulating paper, screening and general construction of the cables were identical.

Each point of the graph represents breakdown of one core, and the arrowed points indicate breakdown of an accessory

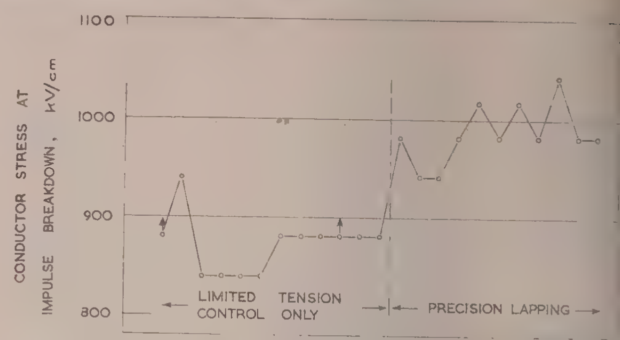

Fig. 5.—Impulse tests on 132 kV 3 × 0·5 in^2 cables, showing the effect of improvements in paper-lapping technique.

and not of the cable itself. It should be noted that, for the earlier tests, control of lapping tensions had already been obtained to a limited extent by modifications to existing machinery, and this accounts for the occasional high value obtained in the tests. No tests on this design of cable had been made before the introduction of even this limited lapping control, but the general level of stress at breakdown for 132 kV cables was previously in the 720–800 kV/cm range. Hence the total increase in breakdown strength due to improvements in lapping technique is of the order of 25%.

(2.3.2) **Processing.**

The normal method of drying and impregnating oil-filled cables is well known, and it is sufficient to note here that considerable improvement in the quality of cables has been achieved during recent years by the use of improved designs of vacuum pump enabling lower residual pressures prior to impregnation to be achieved without recourse to uneconomic processing times. Better economic control of the whole process has also been achieved by the use of more refined methods of measuring the residual gas and water-vapour pressures in the cables prior to impregnation.

A means of eliminating the tedious and costly processing of the already sheathed cable has recently been developed. Drying is carried out in a tank at very low pressures, of the order of 5–10 microns, and the cable is impregnated while still in the tank. This method is not new to oil-filled cables, but an advance has now been made by arranging for the sheathing operation to be carried out with the cable completely immersed in the impregnating oil maintained at a small positive pressure.[9]

Apart from reducing the processing time, the new system presents a number of economic and technical advantages. Thus the length of cables which can be produced is limited only by the size of the tank, and this will permit in many cases reduction in the number of joints required for a cable installation. Furthermore, the size of ducts will be solely decided by the hydraulic requirements of the cable in service, since processing requirements no longer have to be considered.

Tank impregnation allows the use of very-high-impermeability paper and a more compact insulation, there being no bending after drying and before impregnation.[1] Both these factors contribute towards higher electric strength.

Some improvement in power factor is also obtained as a result of the uniformly higher degree of drying of the insulation throughout the length of the cable.

(2.3.3) **Gauge for Measurement of Residual Gas in Oil.**

The gauge for the measurement of residual gas in oil has been used in the manufacture of oil-filled cables since 1935 and was demonstrated at the Exhibition of Instruments and Scientific

laterials, Paris, 1954. The gauge measures the residual presure of gas in a chamber containing a sample of the oil by reading ne pressure existing in a separate chamber adjusted in equilirium with the former. It can also be used as a continuous neasuring reference gauge, using the second chamber set to an cceptable pressure as the standard of reference.

A new version of this gauge has recently been developed Fig. 6). This is of rugged construction and is being fitted in ne transportable oil-treatment plants used in the field.

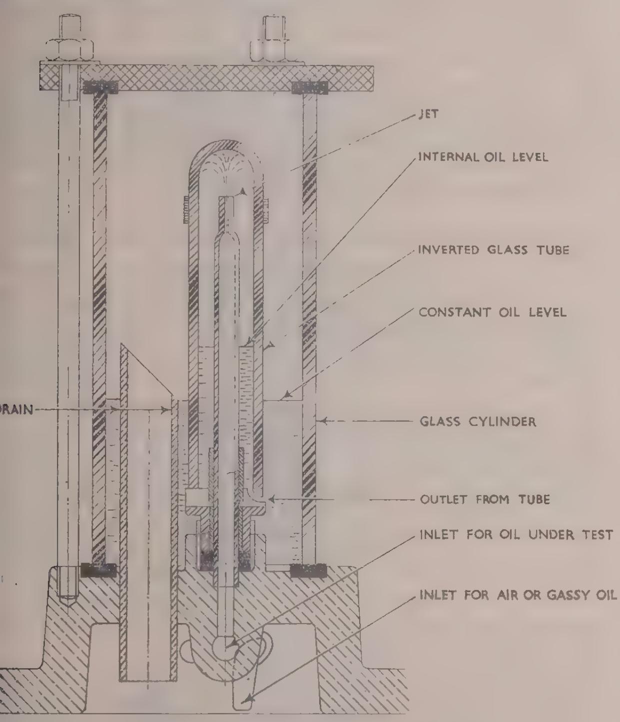

Fig. 6.—Design of oil degasification gauge.

(3) PERFORMANCE TESTS

Tests to which a laboratory assembly of cable and accessories subjected are intended to show its reliability under service onditions for an almost indefinite period. As these tests are of ecessity of short duration, opinions vary as to the nature of ests required and the margins to be met above the working onditions. This is reflected in the type-test specifications dopted in different countries, and even by different authorities vithin one country. Whatever the test specifications, any esponsible manufacturer will ensure that a proposed cable ystem will meet service conditions with adequate margin by eference to his own past field experience coupled with long-term ests and research investigations.

(3.1) Type Tests

In this country, for all types of pressure cables, the type-test equirements have been modified from time to time and the urrent version is open to revision[10] at the end of 1961. A ummary of the tests specified is given in Appendix 10.2.

Many of the tests involved do not reproduce conditions which rise in service. Although this may appear arbitrary, the usefulness of the tests is supported by actual experience, and in the ght of this experience, other useful tests can be devised.

The impulse test is potentially of a semi-destructive nature. It is, in fact, well known that most dielectrics suffer fatigue from repeated high impulse stresses. It should be the object of the impulse test to show that the dielectric of cable and accessories remains unimpaired when repeatedly stressed at the highest impulse voltage which can occur in practice. This aim is clearly not achieved with the test as carried out at present.

Although the oil-filled cable dielectric is less prone to fatigue than most other types of cable insulation, an incipient breakdown may not always lead to a total breakdown because of the small number of impulses which are specified. Hence, either the number of impulses should be increased considerably or a long-term a.c. test should be carried out after the impulse test, at a voltage sufficiently high to change an incipient into a total breakdown. For this reason it has been the authors' practice since 1954 to follow the impulse-withstand test with a 24-hour a.c. test at 2·5 times the working voltage, and experience has shown that this combination meets the requirements stated above, as well as showing up weaknesses in accessory designs which might otherwise pass undetected.

It has been argued that the 24-hour test is too severe and artificial, and that, if universally adopted, it may become restrictive in cable design. The authors cannot agree with this view. Very long experience with pressure cables of all types shows that (*a*) cable systems designed to withstand the 24-hour test have given satisfactory service for up to 30 years, and (*b*) there is experience of some oil-filled cable accessories unable to withstand the 24-hour test, failing on very long-time tests at working voltage. It is worth noting that other equipment, such as capacitor bushings which are not designed to withstand the 24-hour a.c. test, does not have such a good record of service as oil-filled cable systems.

With regard to the alleged restrictive character of this test it should be noted that the type tests listed in Appendix 10.2, especially for the 275 kV rating, take only limited account of a.c. strength. Furthermore, although at present the maximum working stress for which an oil-filled cable insulation can be designed is determined primarily by the impulse voltage test level specified, this limitation may not necessarily apply in future. In fact, the introduction of paper of improved quality, either natural or synthetic, would lead to enhanced impulse strength without necessarily producing a corresponding increase in a.c. strength. With increasing working stresses this could well lead to dangerous cable system designs, and therefore the adoption of a long-term high-voltage a.c. test would act as a desirable safeguard and ensure that further developments would be directed to improvements in both impulse and a.c. characteristics.

The authors do not wish to be dogmatic on the voltage level for the long-time a.c. test. In their experience 2·5 times the working voltage appears to be reasonable, but it is not a precise value which in the light of further experience cannot be either reduced or increased. It is quite certain, however, that the voltage level of the loading cycle test, namely 1·5 times the working voltage reduced to 1·33 times the working voltage for the 275 kV rating, is completely inadequate unless the test is prolonged over a much longer period than at present specified.

(3.2) Behaviour to Switching Surges

It has been generally assumed in the past that the impulse test is adequate to prove the ability of a cable system to withstand all types of surges to which it can be subjected in service, including switching surges and arcing grounds. Investigations have shown that this assumption is not necessarily correct for all types of pressure-cable installation. Further work on this subject is in progress in a number of laboratories, and therefore definite conclusions cannot yet be drawn. On the other hand, it has already been shown that oil-filled cable insulation has more

than adequate strength for switching surges. This is shown by the results given in Table 1, which includes waves representative of switching surges.[11]

Table 1

RELATIVE DIELECTRIC STRENGTH OF OIL-FILLED CABLE INSULATION TO SURGES OF VARIOUS FREQUENCIES

Form of applied voltage	Relative electric strength
1/50 microsec wave	100
50 c/s + 1/50 microsec wave	99
50 c/s + 600 c/s*	85
50 c/s + 2 580 c/s*	85

* Damped waves.

(4) DESIGN FEATURES

(4.1) Compacting of Conductors

For minimum overall cable dimensions the optimum conductor radius varies inversely with maximum working stress, and from this fact stems the increasing attention which is being devoted to compacting conductors to the utmost possible degree compatible with requisite mechanical characteristics. The economic incentive for this action naturally becomes more compelling as conductor cross-section and maximum working stress are increased.

The current design of hollow-core conductor is usually without supporting spiral, and the space gained is utilized to accommodate part of the conductor section. In a design frequently used in this country, the inner layers of the conductor are formed from so-called segmental strips, and the outer layers from flat rounded-edged wires. The alternative construction of conductors entirely formed with segmental strips is also widely used. By these means a solidity of 90–95% can be obtained. Similarly, by rolling or drawing processes the conductors of 3-core cables have been compacted to give solidities of the order of 90%.

(4.2) Aluminium Conductors

Depending on market prices, an overall economy may, in some cases, be obtained by using aluminium instead of copper conductors.

Jointing of aluminium conductors now presents no special problems and can be readily achieved by means of sweated ferrules for which a number of excellent proprietary solders and fluxes are available. An alternative method of jointing conductors by casting the ferrule with molten aluminium has also been used. Work has been in progress for some time on the development of compression joints for aluminium hollow-core conductors, but the long-term ageing test must be completed before the designs can be regarded as proved.

(4.3) Fillerless Cables

Further economies have been effected by the introduction of fillerless 3-core cables, which, although only manufactured in this country since 1954, have been in operation on the Continent much longer. In these cables the conductors are usually shaped, and the interstices between cores are used as oil ducts. If lead sheaths are used with fillerless cables considerable attention has to be paid to maintaining these oil channels, since the greatly reduced internal support results in loss of sheath circularity. Thus, internal pressure treatment is required during application of the reinforcement tapes and also after laying.

(4.4) Aluminium Sheaths

The saving in cost and the improved mechanical performance which are realized by substituting aluminium for lead in the sheathing of oil-filled cables cannot be too strongly emphasized. Whereas at one time the additional cost of the special anti-corrosion protection essential for aluminium sheath made the saving rather marginal, notwithstanding the elimination of reinforcing tapes, the present-day requirement for a similar anti-corrosion protection for all major underground power cables places aluminium for sheathing in a strong position, both technically and economically.

An important advantage which is becoming increasingly valuable in view of the trend towards fillerless 3-core cables is the circumferential rigidity of the aluminium sheath, particularly of the corrugated type, which ensures the retention of the initial oil-flow characteristics, even when installation or other conditions impose heavy mechanical strains on the sheath of the cable.

(5) OVERLOAD CAPABILITIES OF OIL-FILLED CABLES

(5.1) Present Limitations

Unless limited to lower values by economic considerations the current rating of a high-voltage cable is determined by the maximum temperature to which the insulation can safely be subjected. In most types of pressure cable the permissible conductor temperature has hitherto been limited to 85°C, and the rating has been calculated on this temperature. For those cases where the cable has been designed on the basis of continuous loading, this has resulted in the cable having little or no overload capacity. This shortcoming has become particularly noticeable in recent years because of the growing tendency for a cable feeder to be permanently coupled to a transformer. Whereas the transformer can supply quite considerable temporary overloads, the cable has, in the past, prevented this characteristic being exploited unless a larger cable conductor was used than that dictated by normal running conditions.

With most types of pressure cable it is unlikely that the maximum insulation temperature can be raised appreciably because of compound movement, which, on cooling, would give rise to the formation of excessively large voids and consequent destructive ionization. With oil-filled cable, since void formation does not occur the primary problem is whether the dielectric materials can withstand the elevated temperature for sufficiently long periods without affecting the life of the cable. It has been known for a long time that oil-filled cables can be subjected, during the period covered by type-approval tests, to temperatures well above 85°C, but only recently have investigations been undertaken to show whether such temperatures bring about changes in the dielectric, which, in course of time, might adversely affect its reliability. Other factors to be considered are the mechanical behaviour of the cable-system components and the effect of the increased temperature on the medium in which the cable is laid. An experimental programme with these objects, which must clearly take a very long time to be convincing, was started in 1954.

(5.2) High-Temperature Electrical Tests

One part of the investigation, carried out in Italy, was made on samples under strictly-controlled laboratory conditions. This work is being reported elsewhere.[2] The work carried out in England covered cable assemblies for 33 and 132kV. Details of the tests are given in the following Sections.

(5.2.1) High-Temperature Life Tests on 33kV Cable.

A test assembly was erected consisting of three single-core oil-filled cables each about 5yd long and each fitted with two

outdoor-type sealing ends. The conductors were connected in series in a closed loop. All cables had an insulation thickness of 0·13 in, but various combinations of metals were used for conductor and sheath as follows:

Cable (*a*): Copper conductor, 0·30 in^2. Lead sheath.
Cable (*b*): Copper conductor, 0·30 in^2. Aluminium sheath.
Cable (*c*): Aluminium conductor, 0·45 in^2. Aluminium sheath.

The assembly was subjected to the following tests:

(i) 105 daily loading cycles of 8 hours' heating to 120–125° C and 16 hours' cooling. Applied voltage, 19 kV continuously (working voltage).
(ii) 79 daily loading cycles as above. Applied voltage, 28·5 kV continuously (1·5 times the working voltage).
(iii) 556 days continuously at high temperature, 120–125° C (with occasional peaks to 130° C) for five days each week, reduced to 105–110° C at week-ends and during holidays. Applied voltage, 28·5 kV continuously (1·5 times the working voltage).

The higher temperatures quoted above apply to the aluminium conductor cable (*c*).

Dielectric power-factor measurements were taken at intervals during the test, and they showed a gradual improvement over the first 496 days. From then on, the values increased progressively, and on the 740th day, when the test was terminated, the power factor had increased over the original values by approximately 10% at ambient temperature and 25% at 120–125° C.

On examination the insulation of all three cables was found to be in similar condition. As expected the paper had darkened and become embrittled, especially close to the conductor, but very little change was found in the oil. This examination indicated that, although the cables were still serviceable, a breakdown under the test condition could have been expected in the not-too-distant future.

(5.2.2) High-Temperature Life Tests on 132 kV Cable.

Although the above results on 33 kV cables are quite impressive, it will be appreciated that the maximum stress on the insulation of 33 kV oil-filled cables is considerably lower than those now being offered for 132 kV systems, and it was therefore necessary to carry out similar tests on cables for this voltage. In view of the more exacting requirements for such cables, it was decided to apply even more searching tests, in order to detect at what stage the high-temperature operation noticeably affected the dielectric characteristics of the insulation.

The test assembly consisted of a length of 3-core 132 kV cable of 125 kV/cm design stress, together with all types of accessory. The assembly was subjected to the currently specified type-approval loading cycle, thermal stability and impulse tests appropriate to maximum operating temperatures first of 85° C and then 115° C, after which it withstood a sustained high-temperature/high-voltage test for 111 days. During the course of the above tests the soundness of the insulation was proved at intervals by the application of long-term a.c. dielectric security tests at 2·5 times the working voltage for 24 hours—a total of seven such tests being withstood. Power-factor measurements were taken before starting and at frequent intervals during the tests. No significant changes were observed.

Finally an impulse test to breakdown was carried out. A complete summary of the tests is given in Table 2.

(5.3) Effect of High-Temperature Operation on Conductor Joints

In conductor joints it is essential to provide for short-circuit conditions superimposed on those obtaining at maximum operating temperature. From a base temperature of 85° C, pressure-cable conductors are at present permitted to reach 120° C under short-circuit conditions. Hence with a base value in the region of 115–120° C during a sustained overload, the conductor temperature under the same short-circuit conditions would reach about 160° C, and would affect the mechanical strength of sweated ferrule joints of the normal type. The remedy for this is to use either a high-melting-point sweating solder or compression ferrules.

(5.4) Effect of High-Temperature Operation on Sheath Performance

In metal sheaths of lead or lead alloy, recrystallization can occur at 100° C, the extent of crystal growth depending on the nature of the alloy and the amount of prior straining which the sheath has undergone. If such growth results in a sheath grain structure containing very few grains in the wall thickness, the risk of inter-crystalline cracking under conditions of slow straining may be further increased by the higher sheath temperature. Such slow straining can be caused by soil subsidence in the case of buried cable and by expansion movements of cables installed above ground. The development of alloys and extrusion techniques in order to provide sheaths in which crystal growth is negligible when recrystallization occurs has been the subject of prolonged fundamental research, and considerable advances have been made. To obtain the greatest measure of security, however, it is strongly recommended that aluminium sheaths be used on oil-filled cables susceptible to conditions which commonly cause mechanical failure in lead sheaths.

(5.5) Effect of High-Temperature Operation on Servings

By suitable choice of materials, the normal types of anti-corrosion protection can be made suitable for satisfactory operation at the higher sheath temperatures involved. At sheath temperatures above 80° C, the outer hessian serving would in time lose much of its bituminous compound to the surrounding soil, but as the primary function of the hessian is mechanical protection prior to and during laying, and since the life of the hessian even under normal operating conditions falls far short of the life of the cable itself, loss of compound after laying is not a critical factor.

(5.6) Drying out of Soil at High Temperatures

With a conductor temperature of 120° C and a soil thermal resistivity of 120 thermal ohms, it has been estimated that the steady-state sheath temperature of a 3-core 132 kV cable would be 98° C, and for a 3-core 33 kV cable about 110° C. If these conditions were allowed to persist, some drying out of the soil immediately surrounding the cable would occur and the thermal resistivity of many soils will rise to values in excess of those normally used for rating calculations, with the consequent possibility of the cable reaching unduly high temperatures. In such circumstances, provision must be made to keep the thermal resistivity of the dried-out soil sufficiently low. It has been established that backfill sands are available having suitably graded particle sizes to give an acceptable thermal resistivity even when quite dry. In order to avoid risk of sand movement, due, for example, to the action of water, soil subsidence, etc., cables can be embedded in a weak mixture of Portland cement and sand. Extensive experiments have been in progress since early 1959 on a comparison of the thermal behaviour of soil and of a weak sand-cement mixture surrounding cables, with sheath temperature in excess of 110° C. With soils of E.R.A. classifications D and E the preliminary conclusions are that no thermal instability conditions can be established and that the thermal resistivity of the sand-cement mixture appears to follow that of the soil but is always lower.

Table 2

HIGH-TEMPERATURE TESTS ON 3-CORE 132 kV OIL-FILLED CABLE (125 kV/CM DESIGN STRESS) AND ACCESSORIES

Test number	Test	Maximum conductor temperature	Duration number of cycles, etc.	Applied voltage	Proportion of working voltage
	Tests covering 85°C maximum operating temperatures				
				kV	
1	First dielectric security test	Ambient	24 hours	190	2·5
2	First impulse voltage test	85°C	10 positive, 10 negative	640 (Specified withstand)	
			10 positive, 10 negative	660	
3	Second dielectric security test	Ambient	24 hours	190	2·5
4	First loading cycle test	Cycles to 90–94°C	20 daily cycles	114	1·5
5	First thermal stability test	92°C	6 hours' constant load	114	1·5
6	Third dielectric security test	Ambient	24 hours	190	2·5
7	Second impulse voltage test	90°C	10 positive, 10 negative	640 (Specified withstand)	
			10 positive, 10 negative	660 kVp	
8	Fourth dielectric security test	Ambient	24 hours	190	2·5
	Tests covering 115°C maximum operating temperature				
				kV	
9	Second loading cycle test	Cycles to 120°C	20 daily cycles	114	1·5
10	Second thermal stability test	120°C	6 hours' constant load	114	1·5
11	Fifth dielectric security test	Ambient	24 hours	190	2·5
12	Third impulse voltage test	118°C	10 positive, 10 negative	640 kVp (Specified withstand)	
			10 positive, 10 negative	660 kVp	
13	Sixth dielectric security test	Ambient	24 hours	190	2·5
	Long-time, high-temperature/high-voltage tests				
				kV	
14	Sustained high-temperature test	Core 1–120°C, Core 2–123°C, Core 3–134°C	33 days	152	2·0
		Note.—At this stage, owing to a wrong adjustment of the loading current, temperature of all cores increased. Core 3 failed at a temperature of about 160°C			
15	Sustained high-temperature test continued on cores 1 and 2	All three cores at 120°C	78 days	152 (Cores 1 and 2 only)	2·0
16	Seventh dielectric security test	Ambient	24 hours	190	2·5
	High-temperature impulse test to breakdown				
17	Fourth impulse voltage test (taken to breakdown) core 2	117°C	10 positive, 10 negative	640 kVp (Specified withstand)	
			10 positive, 10 negative	660 kVp	
			10 positive, 7 negative	680 kVp	
			Breakdown occurred on 8th negative impulse		
	Same test on core 1	117°C	10 positive, 10 negative	640 kVp (Specified withstand)	
			10 positive, 10 negative	660 kVp	
			2 positive	680 kVp	
			Breakdown occurred on 3rd positive impulse		

Further experimental work is required before final conclusions can be reached.

Artificial cooling can be used to improve ratings under certain conditions, and various experiments are already in progress using different cooling methods.[12]

(5.7) General Conclusions on High-Temperature Operation

The foregoing results and discussion together with the evidenc obtained elsewhere[2] lead to the firm conclusion that, give proper design, manufacture and installation of both cable an accessories, oil-filled cable systems can be subjected to conducto

emperatures up to at least 110° C for considerable periods (and o even higher temperatures for shorter periods) without risk of ailure and without measurable effect on the life of the installa-ion. This feature can therefore be used with complete con-idence as a basis for the assessment of the overload capacity of cable system.

(6) IMPROVEMENTS IN ACCESSORY DESIGN

Improvements in jointing technique and in electrical design ave enabled conventional materials to be used at higher stresses han in the past without reduction in electric strength, and the ntroduction of epoxy resin has permitted a new approach to the lesign of some types of accessory. These factors, together with implification of construction, have led to large reductions in the ize and cost of many accessories. It is worth noting that all il-filled accessories with which the authors are associated are ot only fully type tested to the current C.E.G.B. specification, ut are, in addition, designed to withstand the dielectric security .c. test of 2·5 times the working voltage for 24 hours.

(6.1) Epoxy-Resin Castings in Oil-Filled Accessories

When cast under the carefully controlled conditions essential or use at high electric stresses, quartz-filled epoxy resin com-ines exceptionally good mechanical and electrical properties.[13] ts imperviousness and ability to adhere to metallic surfaces make it an ideal material for use, for instance, as the oil barrier in stop joints. The present cost of epoxy castings is high, and consequently their use has so far been limited to those parts of an accessory where the unique properties of the material can be employed to the best advantage. Examples of the use of epoxy-resin castings are given in some of the accessories described in the following Sections.

(6.2) Straight-Through Joints

The electrical designs of both single and 3-core joints follow a similar pattern. The core insulation is reduced in one or more chamfers between cable screens and ferrule. The ferrule itself, as for all other accessories, is fusiform and is either sweated or of the compression type. The joint is insulated with paper rolls pre-impregnated with oil-filled cable oil, and paper tape is used to fill the spaces on either side of the ferrule and between the chamfered ends of the paper rolls. Joints are screened with copper wires tightly applied to the stress cones and with conducting tape on the cylindrical surfaces. Single-core joints are often required with a break in the earthed screen to make them suitable for cross-bonded systems. In this case the screen is interrupted at the upper end of the stress cones. A small oil gap, maintained by means of insulating spacers, ensures adequate electric strength between the free ends of the screen and the joint casing. Fig. 7 shows a typical joint of this

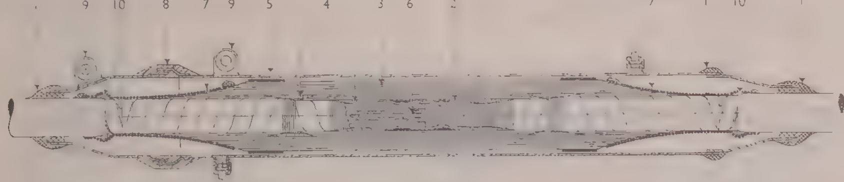

Fig. 7.—132 kV single-core straight-through joint with insulated sleeve (up to 1·0 in²).

1. Wiped joint.
2. Compression-type ferrule.
3. Paper-roll insulation.
4. Paper-tape filling.
5. Copper sleeve.
6. Duct pin.
7. Wire screen.
8. Cast epoxy-resin insulation joint.
9. Bonding lug.
10. Tape poultice.

Conductor size	Dia. of copper sleeve	Overall length
in²	in	in
Up to 0·60	4	38
0·60–1·0	4½	41¼

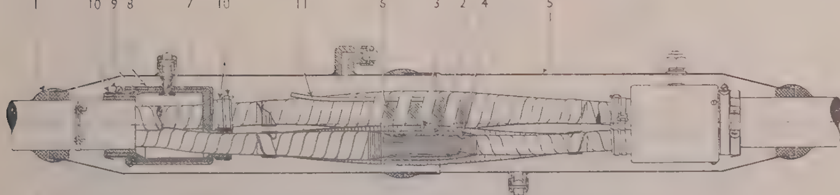

Fig. 8.—33 kV 3-core straight-through joint (up to and including 0·60 in²).

1. Wiped joint.
2. Sweated ferrule.
3. Crepe-paper insulation.
4. Paper-tape filling.
5. Copper sleeve.
6. Copper tinsel screen.
7. By-pass valve.
8. Reinforcing case.
9. Oil-resisting elastomer gland.
10. Hose clips.
11. Earth bond.

Conductor size	Overall length	Dia. of copper sleeve
in²	in	in
0·10–0·20	35	4
0·20–0·40	36	4⅝
0·40–0·60	38	5⅛

type in which the insulation between the two halves of the sleeve is provided by an epoxy casting.

Exceptions to the construction just described are the 3-core 33 and 66 kV designs. These joints are entirely insulated with crepe paper, which has the property of readily adapting itself to uneven surfaces. It gives an equally compact insulation with both circular and shaped conductors, and it is no longer necessary to straighten the cores in order to apply the insulation correctly. This feature permits a considerable reduction in the length of the joint. The 33 kV model is illustrated in Fig. 8. In all cases the insulation diameter is chosen so that the maximum stress in the joint is of the order of 40–50% of the design stress of the cable.

Glove-like glands of oil-resisting elastomer are now used in all 3-core joints to seal the end of the cable to prevent heavy loss of oil during jointing and vacuum treatment. The glands are fitted with simple valves which are opened from outside the joint casing when impregnation of the joint is completed. In all cases the design is such that, once the sheath has been cut and oil flow from the cable commences, the gland is fitted rapidly and secured by mechanical means. By this method the making of wiped joints under heavy oil flow, characteristic of earlier designs, has been eliminated.

(6.3) Stop Joints and Feeding Joints

The introduction of epoxy resin has revolutionized the design of stop and feeding joints and has made possible a 3-core 132 kV stop joint of manageable size. This joint is shown in Fig. 9. It consists essentially of three epoxy-resin bushings clamped into a central barrier plate. The insulation over bushings and cores consists of paper rolls. Three-core stop joints for 33 and 66 kV are similar in general design, but the three bushings are cast into an epoxy central barrier plate so as to form a monolithic construction. As in the case of straight joints the 33 and 66 kV designs are insulated with crepe paper.

Single-core stop joints have a central epoxy-resin casting with embedded stress-control electrodes and barrier flanges. The current design of stop joint for use on 275–400 kV systems is of the double-ended conventional type with epoxy castings replacing porcelain insulators, and with the addition of stress-control electrodes embedded in epoxy resin in the region of the stress cones.

When it is desired to feed oil into the duct of hollow-core cables at a point remote from the sealing ends a feeding joint is used. As seen in Fig. 10, its construction is similar to that of the stop joint with oil channels suitably screened against high stresses provided from joint casing, through the ferrule, to the duct.

(6.4) Trifurcating Accessories

The most economic method of terminating 3-core cables involves the use of splitter boxes and loose pipes fitted over the separated cores. The current design of 132 kV splitter box is shown in Fig. 11. Where the length of tails is excessive a trifurcating joint is necessary. The electrical design of this joint is identical with that of the straight-through joint.

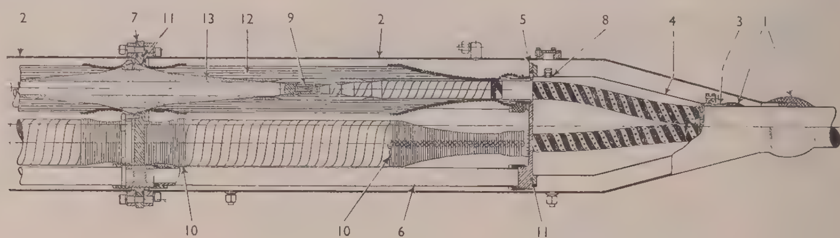

Fig. 9.—132 kV 3-core stop joint (up to 0·60 in²).

1. Wiped joint.
2. Copper casing.
3. Wiping gland.
4. Gland-box casing.
5. Gland plate.
6. Stiffening tubes.
7. Central barrier plate.
8. By-pass valve.
9. Ferrule.
10. Wire screen joined to tape screen.
11. O-ring seals.
12. Paper-roll insulation.
13. Epoxy-resin bushing.

Overall dia.: 13 in.
Overall length: 10 ft 8 in.

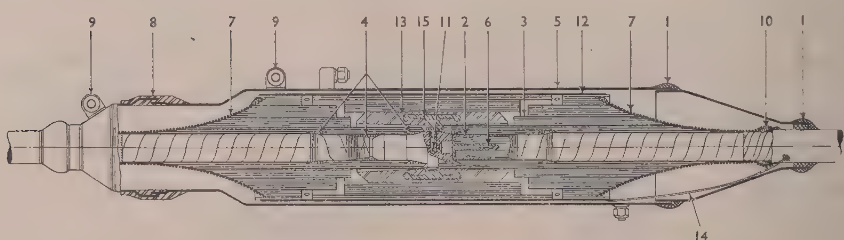

Fig. 10.—132 kV single-core feeding joint with insulated sleeve (up to and including 1·0 in²).

1. Wiped joint.
2. Compression-type ferrule.
3. Paper-roll insulation.
4. Paper-tape filler.
5. Copper casing.
6. Duct pin.
7. Wire screen.
8. Cast epoxy-resin insulation joint.
9. Bonding lug.
10. Tape poultice.
11. Drop valve.
12. Perforated copper screen.
13. Epoxy-resin casting.
14. Earth bond.
15. Embedded metal electrode.

Overall dia.: 7¾ in.
Overall length: 53 in.

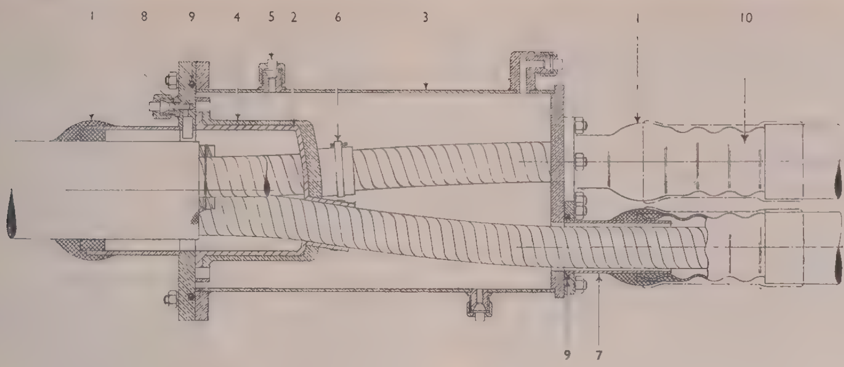

Fig. 11.—132 kV splitter box (up to $0 \cdot 6$ in^2).

1. Wiped joint.
2. Oil-resisting elastomer gland.
3. Copper casing.
4. Reinforcing case.
5. Oil union.
6. Hose clips.
7. Wiping gland.
8. By-pass valve.
9. O-ring seal.
10. Corrugated aluminium pipe.

Overall dia. of copper casing: 8 in.
Overall dia. of O-ring seal: 10¾ in.
Length between wiped joints: 23¼ in.

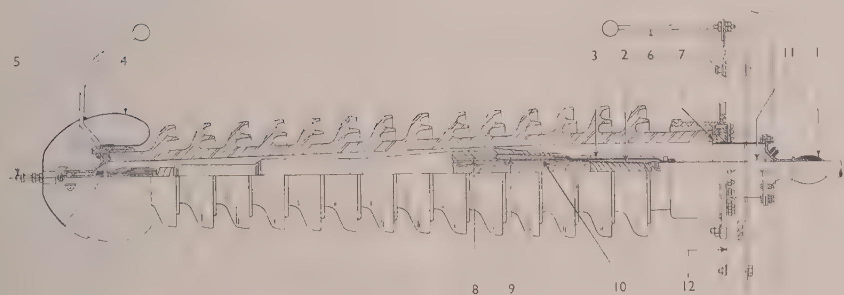

Fig. 12.—275 kV outdoor sealing end.

1. Wiped joint.
2. Wire screen.
3. Supporting gaiter.
4. Corona shield.
5. Connection.
6. Arcing horn.
7. O-ring seal.
8. Epoxy-resin moulding.
9. Embedded metal stress ring.
10. Paper-roll insulation.
11. Reinforcement tube.
12. Teak supporting battens.

Overall length: 11 ft (approx.).
Distance between arcing horns: 76 in.

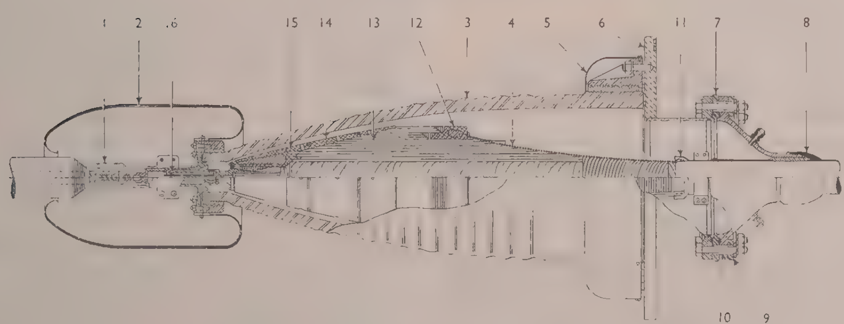

Fig. 13.—400 kV oil-immersed sealing end.

1. Connector.
2. Stress shield.
3. Porcelain insulator.
4. Wire screen.
5. Earthed shield.
6. Base-plate.
7. Insulated joint.
8. Wiped joint.
9. Insulating washers.
10. End bell castings.
11. Supporting gaiter.
12. Epoxy-resin embedded earthed stress ring.
13. Paper-roll insulation.
14. Epoxy-resin casting.
15. Epoxy-resin embedded high-voltage stress ring.
16. Plug-in contact.

Overall length: 6 ft 7½ in (approx.).
Distance between wiped joint and base-plate: 15½ in.
Diameter of base-plate: 29⅜ in.

(6.5) Sealing Ends

Except for the higher voltages, when epoxy-resin components are employed, sealing ends are entirely insulated with pre-impregnated paper rolls and follow normal practice in the use of a stress cone to reduce to a sufficiently low value the stress at the end of the earthed electrode. For 132 kV and above it is necessary to terminate the cone with an insulated stress control ring, the insulation being either paper tape or epoxy resin. Oil-immersed sealing ends for the higher voltage ratings have a stress control ring also at the high-voltage end. This second ring is used primarily to ensure a favourable field distribution without the need for an excessively large insulator cap.[14] Figs. 12 and 13 show the current designs of 275 kV outdoor-type and 400 kV oil-immersed sealing ends. For both designs all stress rings are embedded in epoxy-resin castings.

(6.6) Jointing Techniques

Since the inception of the oil-filled cable, jointing techniques have gradually improved, the aim being to ensure the retention of full impregnation of the cable dielectric. Of particular interest in this respect is the method developed for cutting single-core cables which allows continuous retention of positive pressure in the duct.[15]

Special circumstances sometimes require variations of the normal jointing techniques. In particular, where high static oil pressures are involved, it may be necessary to freeze the cable locally before jointing. This may be done by placing a temporary sleeve around the cable and filling with liquid nitrogen.[16] Where operating ambient temperature and hydraulic design permit the use of oil which solidifies at a relatively high temperature, the more economic method of freezing with solid carbon dioxide can be used. When static oil pressures are exceptionally high and the profile is favourable, the cable is drained and re-impregnated after jointing operations at the high-pressure end are completed. Depending on conditions, draining of the cable can be carried out either at atmospheric pressure or under vacuum. Details of an installation where the first method has been used have been published.[17] With the vacuum process, the cable is partially drained whilst it is being pulled along the down gradient, preferably with a vacuum pump connected to the inner end of the cable on the drum. When laying is completed a head of oil in excess of 1 atm absolute is maintained at the lower end whilst jointing is in progress, and when this is completed the cable is refilled with degasified oil.

(7) ASSESSMENT OF FUTURE POSSIBILITIES

In the preceding Sections a very brief historical résumé of the oil-filled cable system has been given and the more recent developments have been described in greater detail. What of the future? Can the oil-filled cable system be still further developed, so that even more economic transmission installations become possible, or has the ultimate limit now been reached?

The answer to this question from the cable manufacturers' point of view is quite definitely that further progress is possible. There is ample scope for improvements in the paper and oil used for the dielectric and also in the technique of applying the papers and the processes for drying and impregnating them. Higher stresses will inevitably lead to the need for better electrostatic screening of conductors and insulation. Work on these and other projects is already being actively pursued.

Of vital interest is the world-wide search for a low-loss low-dielectric-constant material[18, 19] to replace wood-pulp paper and thus increase the present limit of power which can be transmitted by underground cables.[20] The dimensions of most accessories can almost certainly be still further reduced. The attitude of some cable users towards such developments appears to be less optimistic—an attitude brought about not by any actual increase in incidence of failures in service of the more highly stressed cables, but rather from fear that the margin of safety is being reduced to too low a value. The question of safety margin is, of course, a very important one which merits the most careful attention.

In the earlier days of oil-filled cable development considerable scatter occurred between impulse breakdowns on one test assembly and another. This necessitated a considerable design margin to ensure a successful type test. In addition to increasing the stress at which the various parts can be operated, the improvements already have markedly reduced the scatter of test results. This is not unexpected, since the improvements have resulted from a better understanding of the requirements of oil-filled cable installations, followed by a closer control of the means whereby they can be put into effect. If the spread of test results can be shown to be small, a large design margin over the acceptance test values can only be regarded as uneconomic, and in the absence of other factors, cannot be justified.

One such factor which is frequently quoted as affecting the position is that usually referred to, sometimes rather vaguely, as 'mechanical considerations'. By this is usually implied the ability of cables having thin insulation to withstand the bending hazards to which they may be subjected during handling and laying. It is, of course, true that, if tearing of papers should occur, the effect is likely to be more serious at the higher stresses, but it is also a fact that, provided that the most modern lapping technique is employed, the danger of torn papers is virtually eliminated. The danger from this source is at present considerably less than it was previously with cables of lower operating stress but manufactured under less well controlled conditions.

Another argument brought against carrying development to higher stress levels is that the economies obtainable are so small that the additional risk is not worth taking. It is submitted that this is a very dangerous argument which, if followed to its logical conclusion, would result in developments only taking place if substantial gains could be envisaged. In fact, the history of most types of apparatus is one of steady, painstaking, step-by-step development, producing only moderate economies at any one step. The overall effect of such work over the years results in very worth-while economies which are achieved with no increase of risk to the user.

The conflict of ideas on this subject has now reached the stage when users are reluctant to take advantage of the most advanced cable designs which are available and tend to deplore further developments which might lead to still higher design stresses. Most leading cable manufacturers, on the other hand, hold the opinion, based on the very large amount of detailed information and 'know-how' at their disposal, that the developments so far achieved are entirely sound and that there is no reason why still further advances should not be made. The effect of such developments will be particularly useful for the higher voltages for which oil-filled cables are now being designed, such as 275 kV for the British Supergrid system and 300 and 330 kV for certain oversea installations. Eventually 400 kV and even higher voltages are likely to be required, and the importance of higher operating stresses for such systems will be obvious.

It may safely be assumed, therefore, that developments in oil-filled cables and their accessories will continue, and that more economical designs with entirely satisfactory safety margins will become available. Whilst the user engineers will, quite rightly, approach such developments with caution, there is no doubt that the evidence with which they will be presented should, if examined scientifically in all its aspects, enable them to take full

advantage of the economies offered, with corresponding benefits to their consumers.

(8) ACKNOWLEDGMENTS

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(9) REFERENCES

(1) Gazzana-Priaroggia, P., Occhini, E., and Palmieri, N.: 'A Brief Review of the Theory of Paper Lapping of a Single Core High-Voltage Cable', *Proceedings I.E.E.*, Monograph No. 390 S, July, 1960 (**108** C, p. 25).
Gazzana-Priaroggia, P., Palmieri, N., and Occhini, E.: 'Fundamentals of the Theory of Paper Lapping of a Single Core High-Voltage Cable' (Pirelli 1961).

(2) Gazzana-Priaroggia, P., Palandri, G., and Pelagatti, U.: 'Influence of Ageing on the Characteristics of Oil-Filled Cable Dielectric', *Proceedings I.E.E.*, Paper No. 3348 S, November, 1960 (**108** A).

(3) Gazzana-Priaroggia, P., and Palandri, G.: 'Research on the Electric Breakdown of Fully Impregnated Paper Insulation for High-Voltage Cables', *Transactions of the American I.E.E.*, 1955, **74**, p. 1343.

(4) Salvage, B., and Gibbons, J. A. M.: 'The Impulse Strength of Impregnated-Paper Dielectrics as used in High-Voltage Cables', *Proceedings I.E.E.*, Paper No. 3143 S, December, 1959 (**107** A, p. 405).

(5) Hall, H. C., and Skipper, D. J.: 'The Impulse Strength of Lapped Impregnated Paper Dielectric', *ibid.*, Paper No. 2025 S, April, 1956 (**103** A, p. 571).

(6) Hall, H. C., and Kelk, E.: 'Physical Properties and Impulse Strength of Paper', *ibid.*, Paper No. 2024 S, April, 1956 (**103** A, p. 564).

(7) Palandri, G., and Pelagatti, U.: 'Gli oli Isolanti per Cavi Elettrici', R.C.55 Riun. Assoc. Elettrotec. Ital., Bellagio, 1954, **42**, p. 2.

(8) British Patent No. 815394.

(9) British Patent No. 827410.

(10) B.E.B. Engineering Recommendation C.28/2, August, 1960.

(11) See for instance Johnson, I. B.: 'Switching Surges and Arrestor Performance on High-Voltage Systems', C.I.G.R.É., Paris, 1958, Paper No. 306, and Discussion Group 41, *Proc.* Vol. L, p. 946.

(12) Thoms, D. A., and Holdup, W.: 'Water Cooling of Power Cables', *Electrical Times*, 16th June, 1960.

(13) Gazzana-Priaroggia, P., and Palandri, G.: 'The Use of Synthetic Casting Resins in the Manufacture of very High-Voltage Cable Accessories', C.I.G.R.É., Paris, 1956, Paper No. 215.

(14) Gazzana-Priaroggia, P.: 'Sealing Ends for High-Voltage Cables to be Connected Direct to Transformers or Switch Gear', C.I.G.R.É., Paris, 1954, Paper No. 205.

(15) British Patent No. 711031.

(16) Ashton, A. L.: 'Oil-Filled Cables, Development and Progress', *G.E.C. Journal*, October, 1954.

(17) Pierazzuoli, M.: 'Impianto di Cavi O. F. Posati Verticalmente', *Elettrotecnica*, **43**, No. 3.

(18) deVos, J. C., and Vermeer, J.: 'Contribution to the Development of Power Cables for High and Extra High-Voltage with a Composite Insulation of Synthetic High Polymer Materials and Oils', C.I.G.R.É., Paris, 1958, Paper No. 207 and discussion.

(19) deVos, J. C., and Vermeer, J.: 'On the Impulse Strength of a Composite Insulation of Synthetic High Polymer Materials and Oil as a Dielectric for High and Extra-High Voltage Cables', C.I.G.R.É., Paris, 1960, Paper No. 226 and discussion.

(20) Gazzana-Priaroggia, P., Morello, A., and Palandri, G.: '400 kV Low-Pressure Oil-Filled Cable', C.I.G.R.É., Paris, 1958, Paper No. 202.

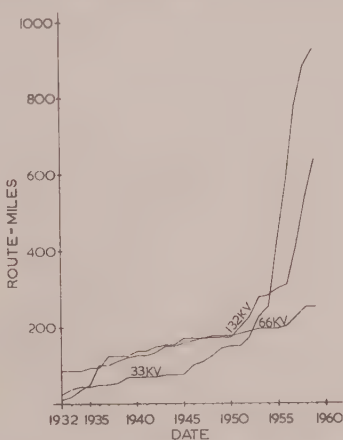

Fig. 14.—Oil-filled cable installed in Great Britain.

Approximate progressive route-miles of single and 3-core cable for 33, 66 and 132 kV systems.

Table 3

Test number	Test	Details	Remarks
1	Bending	Bending cycles followed by voltage-withstand test	
2	Loading cycles	20 daily cycles to 5°C above maximum design temperature at 1·5 times working voltage (1·33 times working voltage for 275kV)	Tests carried out on cable used for test No. 1 to which all accessories have been added
3	Thermal stability	6 hours at constant load (only for 132kV and above)	
4	Impulse withstand	10 impulses for each polarity at specified level and at maximum design temperature*	
5	Power factor and capacitance	Measured as function of voltage between working voltage and twice working voltage	Test at ambient temperature
6	Thermal resistance of dielectric	—	—
7	Hydraulic pressure	On cable sheath 7 days at twice maximum design pressure	
8	Anti-corrosion protection tests	Abrasion and penetration test followed by bending and immersion in saline bath for 100 daily heating cycles to 75–80°C with sheath at 10 volts negative	

* At the request of the engineer, the assembly may at the conclusion of the tests be taken by specified steps (10 positive and 10 negative at each step) to breakdown.

(10) APPENDICES

(10.1) Quantities of Oil-Filled Cables Installed in Great Britain

Fig. 14 shows the progressive total route-miles of oil-filled cable installed in Great Britain from 1932 until 1959 for operation on 33, 66 and 132 kV systems. The remarkable increase in usage for 33 and 132 kV since the early 1950s is noteworthy. An important contribution to the 33 kV usage was the use of oil-filled cables in conjunction with the electrification of the main-line routes of the Southern Region of British Railways. The use of 66 kV cable is now limited to extensions in certain areas where this voltage has been used in the past, and large-scale developments at this voltage are not expected.

(10.2) Type Tests on Pressure Cable Systems

Type tests on cables and accessories supplied to the C.E.G.B. and the Area Boards are in accordance with Engineering Recommendation C 28/2. This specification calls for the tests summarized in Table 3.

Table 4

IMPULSE WITHSTAND TEST VOLTAGES

Rated voltage	Test voltage
kV	kV
33	194
43	239
66	342
132	640
275	1 050

[The discussion on the above paper will be found on page 480.]

621.315.211.3 : 621.315.614.6.017.73

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THE INFLUENCE OF AGEING ON THE CHARACTERISTICS OF OIL-FILLED CABLE DIELECTRIC

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SUMMARY

An investigation has been made of the electrical and mechanical characteristics of the insulation of samples of cables in the range of 60–230 kV after many years of operation in order to evaluate the influence of ageing on the dielectric of oil-filled cables. To determine the effect of thermal ageing alone and in combination with electrical stress, a long series of laboratory tests has been carried out on components of cable insulation, on cable models and on actual cables. A comparison has been made between the laboratory investigations and the state of the insulation of cables after many years of operation.

The following conclusions have been drawn:

(*a*) Paper is the component most affected by temperature.

(*b*) The electric strength is not influenced, within the limits of the tests, by the combined effects of temperature and electric stress.

(*c*) Cables examined after more than 20 years of operation are still in perfect condition and will go on operating satisfactorily for many more years if present loading conditions are maintained.

It is suggested that the mechanical deterioration of paper should be taken as a criterion of the state of used cables and to fix, for both new and used cables, the temperature limits for normal and emergency loading in relation to the desired life of the cable.

(1) INTRODUCTION

Extensive service experience over more than 30 years of oil-filled cables for transmission of electric power at voltages from 30 to 400 kV has proved that the method of designing and calculating the ratings of these cables was carefully chosen. Very often, however, cable makers are questioned by cable users who would like to have a better knowledge of the permissible temperatures, frequency and duration of emergency loading in relation to the desired life of the cable and the desired reliability of service. In other words, cable manufacturers are asked whether they know how many years of life a cable will lose by short periods of overloading.

The makers are not generally inclined to accept, even for very short periods, higher temperatures than those so far accepted, even though desirable for improved operation of the system. This reluctance is justified by the fact that, very often, precise data on many factors which can affect the cable temperature are not available and the probability of hot spots along the route is increased by increasing the temperature. This state of affairs has sometimes led to more costly installations which are, of course, inefficiently exploited.

An important case is represented by cables connected to transformers for which a 30% overload capacity for many hours is admitted and it would be desirable for the cables to have an equal capacity for overload. If the cables were of limited length, artificial cooling could be provided to enable them to carry the same overload as the transformer without undue temperature rise. It is not, however, within the scope of the paper to deal with this particular aspect of the problem but to deal in a more general way with the consequences of higher operating temperatures.

The investigation covered in the paper is limited to the dielectric of the oil-filled cable and mainly examines the possibilities of cables manufactured according to present practice.

The effect of temperature on insulating materials is well known to cable engineers. The Engineering Standards Committee of Great Britain made careful tests in 1905 on Manila paper and other insulating materials, establishing a relation between equivalent weeks of continuous heating and the deterioration of the paper expressed as a percentage of the original shearing strength.[4] In 1913 Steinmetz and Lamme in the United States presented a paper giving general information on the behaviour of different insulating materials, including paper insulation, which was taken as a basis for the preparation of the standardization rules on cables issued by the American I.E.E. Standards Committee in 1916.[4] Since then many authorities[1–5, 7] have investigated the problem, but it was, however, considered that further work would be of interest for an improved knowledge of the matter.

The present paper takes into consideration problems relating only to the insulation of the cable and does not deal with other problems such as those relating to cable sheaths, accessories, laying conditions, etc., which all have to be considered if operating temperatures higher than those accepted up till now are to be adopted. These problems, however, can all be solved with less difficulty.[7]

In our investigation a few samples of cable which had been in operation for many years were examined and carefully tested. It was very useful to know the present state of such cables because very interesting information about the possibility of more efficient utilization was collected. Unfortunately it was difficult to correlate the state of cables with their actual load in service because too many data were missing. It was found, however, that all the cables examined after more than 20 years of perfect operation were still in quite satisfactory condition from the electrical point of view.

Following the examination, many laboratory investigations were carried out to obtain a better knowledge of the phenomena which lead to alteration of the dielectric due to the combined effects of temperature and electric stress.

(2) EXAMINATION OF CABLES AFTER MANY YEARS OF OPERATION

A series of examinations was carried out on samples taken from feeders in actual service. Some of the cables (operating in the Paris networks) were taken out of operation purely for testing purposes, and some because of oil leaks due to lead-sheath fractures. The investigations were carried out on the following oil-filled cables:

Cable A.—Single-core 475 mm² 63 kV, laid in Paris in 1932.

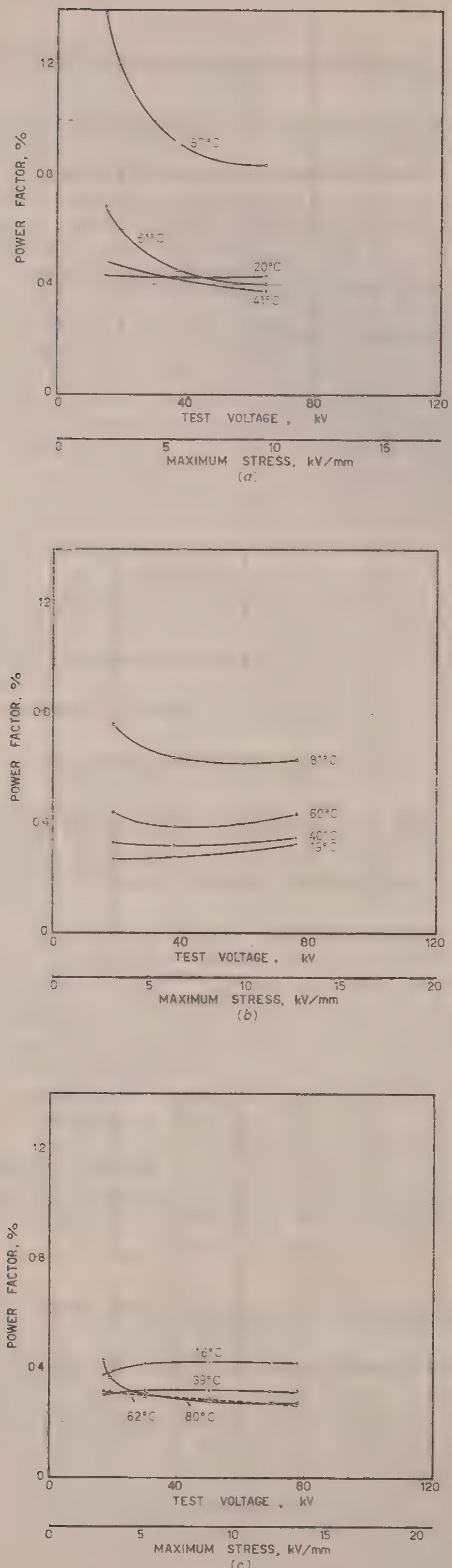
The authors are with Pirelli S.p.A., Milan, Italy.

A length of 30 m of cable was cut in 1955, for testing purposes only, near the Harcourt substation from a line in quite satisfactory operation and was replaced with a length of new cable.

Cable B.—Single-core 140 mm² 66 kV, laid between Vigliena and Poggioreale substations (Naples) in 1935. In 1943 the cable was damaged by bombing at many points and was left without any oil feed until 1946. The cable was then repaired, refilled with oil and put in operation again in 1947. In 1955, a length of 25 m, which had to be replaced owing to an oil leak in the lead sheath, was taken back to the factory for testing.

Cable C.—Single-core 90 mm² aluminium conductor, 60 kV, laid in Genoa in 1943. A length of 140 m, which had to be replaced in 1957 because of the yielding of one pillar of a bridge along which the cable was laid, was taken back to the factory for testing.

Cable D.—Three-core 190 mm² (0·3 in²) tinned-copper conductor, 66 kV, laid in Sunderland in 1931. Owing to gassing



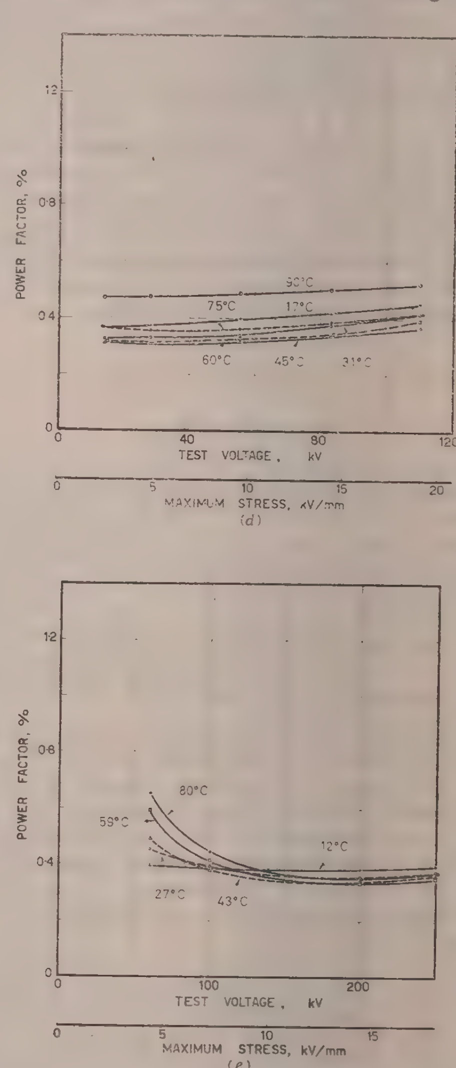


Fig. 1.—Power-factor/voltage curve for various cables after many years of operation.

(*a*) Cable A.
(*b*) Cable B.
(*c*) Cable C.
(*d*) Cable D.
(*e*) Cable E.

rouble the oil was changed by flushing the cable through with oil containing naphthalene.

In 1943 the cable was damaged by bombing, repaired and illed with fresh oil. In 1947 fractures of the lead sheath began o occur on a part of the cable laid along a steel bridge.

Between 1947 and 1958, the year in which the faulty length was replaced, approximately 400 gal of new oil were pumped nto the tank feeding the cable. The faulty length was taken back to the factory for testing.

Cable E.—Single-core 350 mm^2 225 kV, laid between Clichy-sous-Bois and Saint-Denis substations (Paris) in 1936. A ength of 30 m was cut from the line in 1956 for testing and was eplaced with a length of new cable.

(2.1) Examination of Oil Samples

The determination of acidity and power factor of the oil drawn from sealing ends or stop-joints of cables in operation proved to be unreliable unless carried out with particular care, because of pollution by heavy oils used in the past for impregnation of the paper employed for the hand-applied insulation of these accessories.

Many determinations of the acidity and power factor were carried out on oils drawn from cables, but, in all except one case, no significant information on the condition of the cable was obtained. Only once, in Paris, owing to particular route conditions and by using great care, was it possible to draw from the cable the oil actually present in the central duct, and the information obtained was significant.

(2.2) Tests on Used Cables

The tests on cables consisted of:

(i) Measurements of variation of power factor with voltage at various temperatures.
(ii) High-voltage a.c. and impulse tests.
(iii) Acidity and power-factor determination on oil taken from the cable duct.
(iv) Determination of the mechanical characteristics of the paper.

Fig. 1 shows the power-factor/voltage curves at various temperatures for the different cables.

Table 1 summarizes the results of the tests on paper and oil and the high-voltage a.c. and impulse tests. Unfortunately it was impossible to obtain sufficient data to evaluate the actual load of the lines from which the cables were taken. The only available data relate to the 225 kV Paris cable, for which the monthly maximum power peaks and the total amount of power transmitted during the period March, 1946, to August, 1955, were known.

From these data the very approximate diagram shown in Fig. 2 was deduced. This is the result of a calculation in which many assumptions had to be made about the power factor of the system, daily load factor and seasonal variation of the thermal characteristics of the soil. The diagram, which is therefore purely indicative, is, however, interesting because it shows that the temperature of 85° C, i.e. the maximum permissible operating temperature for which the cable was designed, was probably never reached. From the data of Table 1 and curves of Fig. 1 the following conclusions can be drawn:

(*a*) The actual condition of the cables was quite satisfactory.

(*b*) Although exact data on the original characteristics are not known, no appreciable mechanical deterioration of the paper was observed, except in the case of cables D and E, where a very moderate deterioration seems to have occurred. The rather

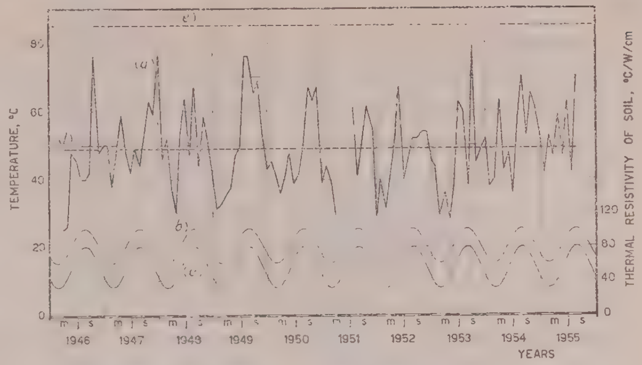


Fig. 2.—Maximum conductor temperature of the 225 kV o.f. cable laid in Paris in 1936, calculated from the monthly power peaks.

A daily load factor having a mixed rectangular and sinusoidal shape of 0·75, and a power factor of 0·9 have been assumed.

(*a*) Calculated maximum conductor temperature.
(*b*) Assumed soil thermal resistivity.
(*c*) Assumed soil temperature.
(*d*) Calculated mean conductor temperature.
(*e*) Maximum permissible temperature.

low folding-strength figures for the paper of cable C are fully justified because the paper was manufactured in war time with inferior-quality pulp.

(*c*) Examination of the oil drawn from the cables did not give useful information. In the case of cable E, the oil tested, being drawn from a short length of cable, came from the reservoir connected to the cable. This oil did not contain acid products but did contain metal soaps or other products which impaired the power factor. The same applies to cable D.

(*d*) A moderate increase of power-factor/voltage at various temperatures in comparison with power factors measured on new cables manufactured in the same period was observed. Power-factor variations up to 30% were found at 80° C and at the operating voltage. All the cables examined, except C and E, which are made with low-loss (water-washed) paper, were made with papers of standard quality.

(*e*) The power-factor curves, particularly those measured at the highest temperatures, are characterized by the negative power-factor difference.[19, 20] Only the 3-core cable, D, does not have this characteristic, but the large amount of new oil pumped into it during operation may have contributed in some way to create particular conditions.

(*f*) The phenomenon of the inversion of the relative position of the power-factor curves measured at various temperatures is not as evident as in the case of plane capacitors, as shown in Section 3. It should be pointed out, however, that a thermal gradient is present inside a cable insulation and different behaviour and changes occur in different layers, thus rendering difficult a quantitative comparison with uniformly aged laboratory models.

(*g*) The high-voltage a.c. and impulse test results confirm the laboratory tests, demonstrating that the combined effect of temperature and electric stress does not affect the oil-filled cable insulation as far as electric strength is concerned. In fact, all cables withstood the 24-hour test at a voltage corresponding to 2·5 times the working voltage (E_0) or higher and the breakdown stress values at impulse are very good, taking into account the date of manufacture. The relatively low maximum stresses at breakdown obtained in the a.c. long-time test for cables A and B, if compared with those obtainable today on similar cables, are to be ascribed only to lack of screening on the outside of the insulation.

Table 1—Summary of Tests Carried out on O.F. Cables After Many Years of Operation

Designation of cable	Oil tests: Acidity	Oil tests: Power factor at 100°C	Paper tests*: Thickness	Paper tests*: Number of folds to fracture	High-voltage test, breakdown voltage: Impulse	High-voltage test, breakdown voltage: Alternating	Remarks
	mg KOH/g		mm		kV	kV	
A 63 kV 1 × 475 mm² Maximum working stress 5·4 kV/mm	0·16	0·0341	0·11	5 150 mean 4 000 min 5 900 max	—	150(*a*)	(*a*) Breakdown occurred 6 h 30 m after application of voltage (maximum stress at breakdown 21·8 kV/mm corresponding to $4E_0$). At the end of test the temperature of lead sheath was 50°C (ambient temperature 28°C). Evidence was found of ionization in the oil gap between outer surface of the cable insulation and lead sheath. The cable had no metallized-paper screen over insulation. Before breakdown test the sample had been submitted to a 24-hour test at 100 kV corresponding to $2{\cdot}7E_0$
			0·14	4 650 mean 2 900 min 5 800 max			
B 66 kV 1 × 140 mm² Maximum working stress 6·35 kV/mm	(*a*)	(*a*)	0·08	2 832 mean 1 863 min 4 015 max	—	150(*b*)	(*a*) Sample returned to factory empty of oil due to lead sheath fractures. A sufficient length with sound sheath was refilled with new oil for test (*b*) Breakdown occurred 7 hours after application of voltage (maximum stress at breakdown 25 kV/mm corresponding to $3{\cdot}9E_0$). At the end of test the temperature 1 m from breakdown point was 80°C (ambient temperature 26°C). Evidence was found of ionization in oil gap between outer surface of cable insulation and lead sheath due to lack of a metallized-paper screen over cable insulation Before breakdown test the sample had been submitted for 24 hours to 110 kV ($2{\cdot}9E_0$), 4 hours to 130 kV, 4 hours to 140 kV
			0·11	4 640 mean 1 400 min 8 000 max			
			0·14	10 700 mean 5 300 min 12 970 max			
C 60 kV 1 × 90 mm² Maximum working stress 5·9 kV/mm	0·5	0·008	0·08	992 mean 827 min 1 413 max	550, maximum stress 94 kV/mm (*b*)	24 hours at 150 kV ($4{\cdot}33E_0$) no breakdown (*a*)	(*a*) Before the 24-hour test, the sample had been submitted to 60, 80, 100 and 120 kV (15 hours per step) (*b*) Impulse test was carried out on the same sample submitted to the 24-hour test at 150 kV. Test was carried out from 350 kV in steps of 25 kV, applying at each step 10 positive and 10 negative shots. Breakdown occurred at 550 kV negative polarity after having passed the 10 impulse test with positive polarity
			0·11	2 366 mean 1 876 min 3 020 max			
			0·13	2 134 mean 1 120 min 2 863 max			
D 66 kV 3 × 0·3 in² Maximum working stress 6·7 kV/mm	0·05	0·045	0·1	White core 1 260 mean Red core 1 246 mean Blue core 1 166 mean	Blue core 550 (*a*) Red core 550 (*b*)	White core 195 (*c*)	(*a*) Breakdown in trifurcating box; positive polarity (maximum stress 96·8 kV/mm) (*b*) Breakdown in the cable; positive polarity (maximum stress 96·8 kV/mm). The impulse test was carried out at 21·5°C starting from 350 kV in steps of 25 kV applying at each step 10 positive and 10 negative shots (*c*) The white core was tested for 24 hours at 96·5 kV ($2{\cdot}5E_0$). Voltage was then raised by steps of 10 kV of 4 hours duration, up to 195 kV. Breakdown in cable occurred after 3 hours (maximum stress 34·2 kV/mm) Blue and red cores were submitted to 80 kV for 16 hours before impulse testing
			0·13	White core 1 474 mean Red core 1 516 mean Blue core 1 849 mean			
			0·2	White core 7 360 mean Red core 6 390 mean Blue core 7 150 mean			
E 225 kV 1 × 350 mm² Maximum working stress 9·4 kV/mm	0·06	0·09	0·1	1 719 mean 1 688 min 1 837 max	1 100, maximum stress 80 kV/mm (*a*)	24 hours at 350 kV ($2{\cdot}65E_0$)	(*a*) Impulse test was carried out on same length submitted to the 24-hour test, starting from 900 kV in steps of 50 kV each, applying 10 positive and 10 negative shots at each step. The cable withstood 10 positive shots at 1 100 kV and broke down during test with negative polarity at same level
			0·12	2 975 mean 2 488 min 3 450 max			
			0·15	3 958 mean 3 100 min 5 070 max			
			0·19	7 254 mean 5 840 min 8 950 max			

* The paper tapes before testing were extracted with petrol ether and then conditioned for 24 hours at 65% r.h. and 20°C

(3) LABORATORY INVESTIGATION

The investigation consisted of evaluating, by means of accelerated life tests, the effect of temperature alone, and the combined action of temperature and electric stress.

In order to isolate the various factors and to evaluate their partial effects, tests were carried out on the two components of the cable insulation (oil and paper) separately and in combination. The contribution to the process of alteration of the dielectric given by the different metals present in cables was separately investigated.

(3.1) Effect of Temperature only

Many tests were carried out at temperatures higher than those which, according to the present practice, are considered as the maximum permissible. Temperatures above 140° C were, however, disregarded because at this temperature the deterioration process of the cellulose has already rather different characteristics and the speed of reaction is too high to be easily controlled.

To determine the influence of metals on the deterioration process, the following metals which may be present in oil-filled cables were taken into consideration: copper, tinned copper, aluminium, lead, and mild steel (oil-duct spiral). The tests carried out in the presence of lead and mild steel are not reported in this paper because their effect on the alteration of the oil and paper was practically nil. All the tests were performed in conditions strictly similar to those existing in cables, i.e. in the absence of air and moisture.

To evaluate the effect of temperature and to determine the rate of deterioration, test methods were preferred which, according to previous investigations[1, 2] and confirmed by the authors' experience, have more practical interest, give more consistent results and can be more easily carried out.

To evaluate the effect of thermal ageing on paper the following tests were adopted:

(*a*) Number of double folds to fracture (Schopper folding test apparatus).
(*b*) Tearing strength (Elmendorf apparatus).
(*c*) Power factor (measured at 100° C on the dried paper).
(*d*) Impermeability.

Other apparently more scientific methods like the determination of copper number or the variation of cellulose viscosity[12] were disregarded because, apart from their complications, they give results which are not always correlated with the mechanical properties of the paper and they can lead to misleading interpretation if not performed with extreme care.[13]

To evaluate the rate of thermal alteration of the oil the variation of viscosity, acidity, and power factor at 100° C were determined.

The thermal ageing of the composite oil-impregnated paper dielectric was evaluated from the variation of power factor with voltage at different temperatures in a plane capacitor and from the variation of characteristics of paper and oil separately, according to the methods mentioned.

(3.1.1) Characteristics of Material used for Tests.

Cable Oil.

Specific gravity	0·89
Flash point (open cup)	155° C
Aniline point (A.S.T.M. D611–55T)	75° C
Acidity value, mg KOH/g oil	<0·03
Viscosity at 20° C	27 cS
Viscosity at 50° C	8 cS
Pour point (A.S.T.M. D97–47)	−45° C
Power factor at 100° C	0·0005 — 0·001
Hydrogen absorbed at 80° C and 16 kV after 300 minutes (Pirelli method)	1·3 cm³

*Cable Paper (Kraft Pulp).**

Density	0·76 g/cm³
Thickness	0·11 mm
Weight	80 g/m² nominal
Impermeability, Emanueli units	2 × 10⁶
Impermeability, Gurley seconds	300
Ash	<0·41%
Breaking length	8 km
Elongation at break	3%
Schopper folding strength, double folds (A.S.T.M. D643–43)	3000
Elmendorf tear resistance (force in grammes required to tear a specimen (A.S.T.M. D689–44)	140

All mechanical tests were carried out at 65% r.h. and 20° C.

Copper.—99·9% annealed electrolitic copper wire, diameter 0·9 mm. Brilliant surface and carefully degreased.

Tinned copper.—Copper wire as above, tinned by hot tinning process and carefully cleaned.

Aluminium.—99·5% annealed aluminium wire, diameter 0·9 mm, carefully degreased.

(3.1.2) Method and Apparatus.

To obtain the required conditions during ageing, i.e. absence of air and moisture, the samples were sealed in neutral glass test tubes using the apparatus illustrated in Fig. 3. The paper

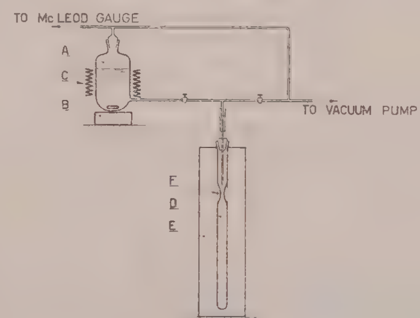


Fig. 3.—Apparatus for filling test tubes under vacuum.

A Oil degasifying vessel.
B Magnetic stirrer.
C Electric heater.
D Test tube.
E Thermostatically controlled heating bath.
F Constriction for flame sealing.

(made into small rolls and dried for 24 hours at 100° C) and, when present, the metallic wire wound on the paper roll, were introduced into the test tube D which was then flame restricted at F, and connected to the apparatus. After the application of vacuum at 100° C for 6 hours the degasified oil was finally allowed to fill the test tube. The degasification was carried out by stirring under vacuum for 1 hour at 60° C. The test tube after filling with oil was kept for another hour under vacuum at 100° C, and then, still under vacuum, was flame-sealed at the constriction.

The electric ovens used for heating the test tubes were of the forced-air-circulation type (maximum temperature difference, ±1° C) equipped with temperature-recording instruments.

The tests were carried out at 90, 100, 110, 120, 130 and 140° C for different periods up to 4 years.

When two or more materials were tested together the following proportions by weight were maintained:

oil/copper	4/3	oil/aluminium	4/1
oil/paper	4/1	oil/paper/aluminium	4/1/1
oil/paper/copper	4/1/3		

* A single-ply paper having mechanical characteristics similar to those used many years ago was chosen for the laboratory investigation, in order to have a better comparison with the information obtained from the examination of cables after many years of operation.

The relative proportions are quite different from those present in cables, especially as regards the oil. They have, however, been considered advisable in order to perform all the required tests, avoiding the testing of oil obtained by solvent extraction from the paper.

(3.1.3) **Test Results on Dielectric Components.**

(3.1.3.1) *Tests on Oil Alone.*

The oil after heating in the absence of air at temperatures from 100°C to 140°C, even for very long periods, does not show any appreciable variation in viscosity, acidity or power factor.* Table 2 shows some of the results obtained.

Table 2

Effect of Heating Cable Oil in the Absence of Air in Sealed Containers

Temperature	Period of ageing	Viscosity at 30°C	Acidity	Power factor at 100°C
deg C	days	centistokes	mg KOH/g	
—	—	17·1	<0·03	0·0007
100	180	17·1	<0·03	0·0011
120	90	17	<0·03	0·0015
120	180	17·1	<0·03	0·0012
140	8	16·9	<0·03	0·0009
140	30	17	<0·03	0·0016

(3.1.3.2) *Tests on Paper Alone.*

The heating of paper, even in the absence of air, affects its mechanical characteristics. Deterioration increases with temperature and heating time. The curves of Figs. 4 and 5 show,

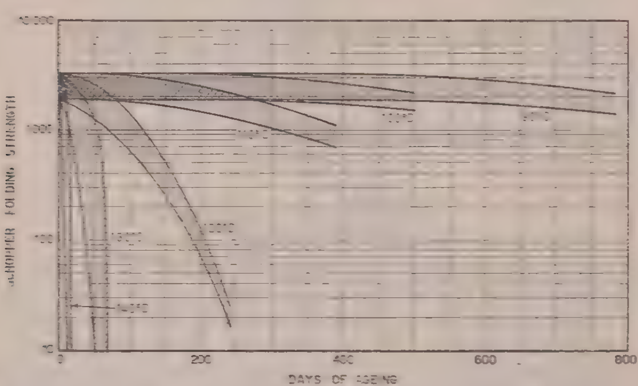


Fig. 4.—Schopper folding strength of cable paper as affected by ageing in absence of air in sealed containers at different temperatures.

for the type of paper mentioned in Section 3.1.1, the deterioration in folding and tearing strength with heating time in the range 90°–140°C. Notwithstanding the spread, which is normal for tests of this type, the figures can be considered as reliable and significant, being based on a large number of tests.

It has been confirmed that the mechanical deterioration of the paper due to heating is caused by a severe chemical change. The mechanism of deterioration of the cellulose, according to the most recent opinions[12, 14] is rather complicated and not completely explained. It seems that it starts with a hydrolysis process and goes on with an oxi-reduction reaction. In this process water and partially gaseous acid products are developed. The latter were particularly abundant after the tests at the highest

* The power-factor measurements are carried out in a test cell with a stress of 0·5kV/mm.

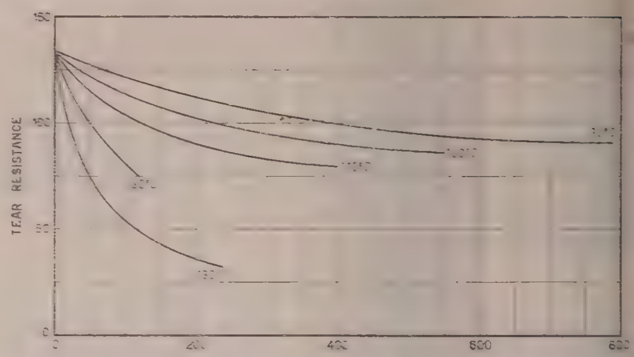


Fig. 5.—Elmendorf tear resistance of cable paper as affected by ageing in absence of air in sealed containers at different temperatures.

temperatures. The formation of acid products in the thermal decomposition of paper has been confirmed by tests carried out in different laboratories.[6, 9, 12, 17] These acid products can be extracted from the paper using special solvents or simply thin cable oil.

It should be mentioned that the acidity values are certainly underestimated. In fact it has been found that most of the acid products consist of high-molecular-weight acids, but, in addition to these, volatile acids are also present. The latter may be easily lost in pouring the oil from the test tubes and during subsequent handling for measuring purposes. The presence of heavy-molecular-weight acids has also been confirmed in oils taken from oil-filled cables after many years of operation. In Table 3 some acidity values are shown for oil extracts made

Table 3

Acidity due to Thermal Degradation of Paper Determined by Extraction by Cable Oil

Temperature	Period of ageing	Acidity
deg C	days	mg KOH/g
120	60	0·11
120	90	0·21

at 40°C on paper aged alone in sealed containers in the absence of air (ratio oil/paper, 2/1).

The power factor of the paper and its impermeability, on the other hand, remain practically constant, even after long periods of heating at high temperature (two months at 130°C or six months at 120°C).

(3.1.3.3) *Tests on Oil-Impregnated Paper.*

The effect on the paper of heating in the presence of oil and in the absence of air and moisture is exactly the same as that observed in the tests on the paper alone described in the previous Section. As far as the oil is concerned, no change in power factor or viscosity has been noticed, as in the case of oil heated alone, but an increase in the acidity has been observed (see Table 4).

To establish if this acidity was due to oxidation of the oil produced by oxygen yielded by the paper, or simply to the solution of acid products developed during the deterioration of the paper, the same tests were repeated by using silicone D200/20 fluid. This fluid is much more oxidation-resistant than mineral oils and this has been confirmed by comparative tests carried out using ozone as the oxidizing agent.

The acidity determined on silicone fluid after heating in the

Table 4

EFFECT OF THE PRESENCE OF PAPER ON POWER FACTOR AND ACIDITY OF OIL AFTER PROLONGED HEATING IN THE ABSENCE OF AIR

Test conditions	Temperature	Period of ageing	Acidity	Power factor at 100° C
	deg C	days	mg KOH/g	
Without paper ..	120	120	<0·03	0·001
With paper ..	120	120	0·3	0·002
Without paper ..	130	25	<0·03	0·001 5
With paper	130	25	0·2	0·002 5

presence of paper was found to be the same as that determined on cable oil in tests carried out under exactly the same conditions (2 months at 120° C).

It is therefore evident that the increase of acidity determined on the cable oil after prolonged heating in the presence of paper is due to degradation of the paper and not to the alteration of the oil.

In order to investigate more fully the thermal degradation of the paper, other types were examined, namely laboratory-made papers prepared with unrefined groundwood, bleached cotton linters and softwood (kraft) pulp bleached by the chlorine-dioxide process (96% α-cellulose).

The results of the tests carried out on these types of paper in the presence of oil and in the absence of air at 120° C for up to 4 months are illustrated in Fig. 6. From these data the acidity

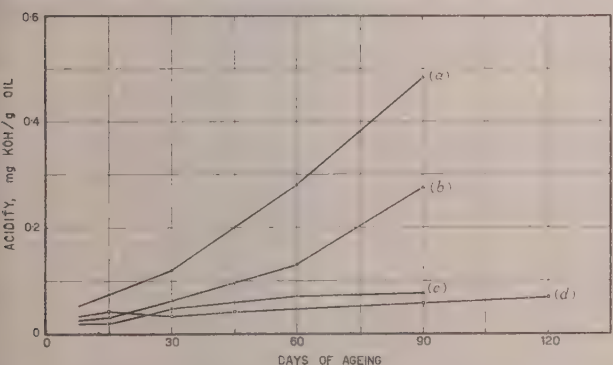


Fig. 6.—Effect of ageing under oil in absence of air in sealed containers at 120° C on acidity formation of different types of cellulose papers.

(a) Groundwood paper.
(b) Cable paper (Kraft grade).
(c) Bleached cotton linters paper.
(d) Softwood bleached pulp paper.

formation appears to be dependent on the degree of cellulose purity. Unfortunately it was not possible to obtain comparable data of the degradation in mechanical strength because the papers were in the form of laboratory-made sheets. The influence of the degree of purity of the paper on its thermal degradation is worth further investigation.

These tests confirmed that the power factor of the oil impregnating the paper does not appreciably change during heating, also in the case of groundwood paper. In this connection it is worth mentioning that the addition of organic acids to cable oil, even in large proportion, produces only a very small increase in its power factor. Table 5 shows the power factor and acidity of cable oil to which organic acids in different proportions have been added.

Table 5

EFFECT OF ADDITION OF ORGANIC ACIDS ON THE POWER FACTOR OF CABLE OIL

Type of acid	Quantity	Calculated oil acidity	Power factor at 100° C
	%	mg KOH/g	
None	—	<0·03	0·000 7
Oleic acid ..	0·036	0·07	0·002 5
Oleic acid ..	0·25	0·5	0·002 5
Stearic acid ..	0·25	0·5	0·001 1

(3.1.3.4) *Tests on Cable Oil in the presence of Copper.*

The effect on cable oil of heating in the absence of air and in the presence of copper is an appreciable increase of power factor.

No change in acidity and viscosity measurable by ordinary methods has been observed in tests carried out at temperatures between 100° C and 140° C for different times. Some typical results after prolonged heating in the absence of air in sealed containers are shown in Table 6.

Table 6

EFFECT OF THE PRESENCE OF METALS ON THE POWER FACTOR AND ACIDITY OF CABLE OIL

Metal	Temperature	Period of ageing	Acidity	Power factor at 100° C
	deg C	days	mg KOH/g	
None	100	—	<0·03	0·000 5
Copper	100	180	<0·03	0·085
Copper	120	90	<0·03	0·050
Copper	120	180	<0·03	0·080
Copper	140	4	<0·03	0·065
Tinned copper ..	140	4	<0·03	0·003 5
Copper + copper passivator	140	4	<0·03	0·000 1
Aluminium ..	140	4	<0·03	0·000 5

The action of copper in the alteration of mineral oil when heated in the presence of oxygen is well known, and generally this alteration is thought to be related to the presence of copper ions in the oil. Although known,[18] the action of copper ions in the absence of oxygen is less evident. It has been found, however, that the very small amounts of oxygen which may be present in a cable oil as peroxide or acids are quite sufficient to explain the results obtained.

As regards the acidity determination, the standard analytical methods are not very sensitive and acidity values much lower than the limit of sensitivity of these methods can produce amounts of copper soaps quite sufficient to impair the power factor of the oil after ageing, even in the absence of air.

Table 7 shows the effect of the addition of copper soap (copper

Table 7

EFFECT OF ADDITION OF COPPER OLEATE ON THE POWER FACTOR OF CABLE OIL

Copper oleate concentration	Power factor at 100° C
%	
0	0·000 5
0·02	0·028 0
0·2	0·144 0
2	0·250 0

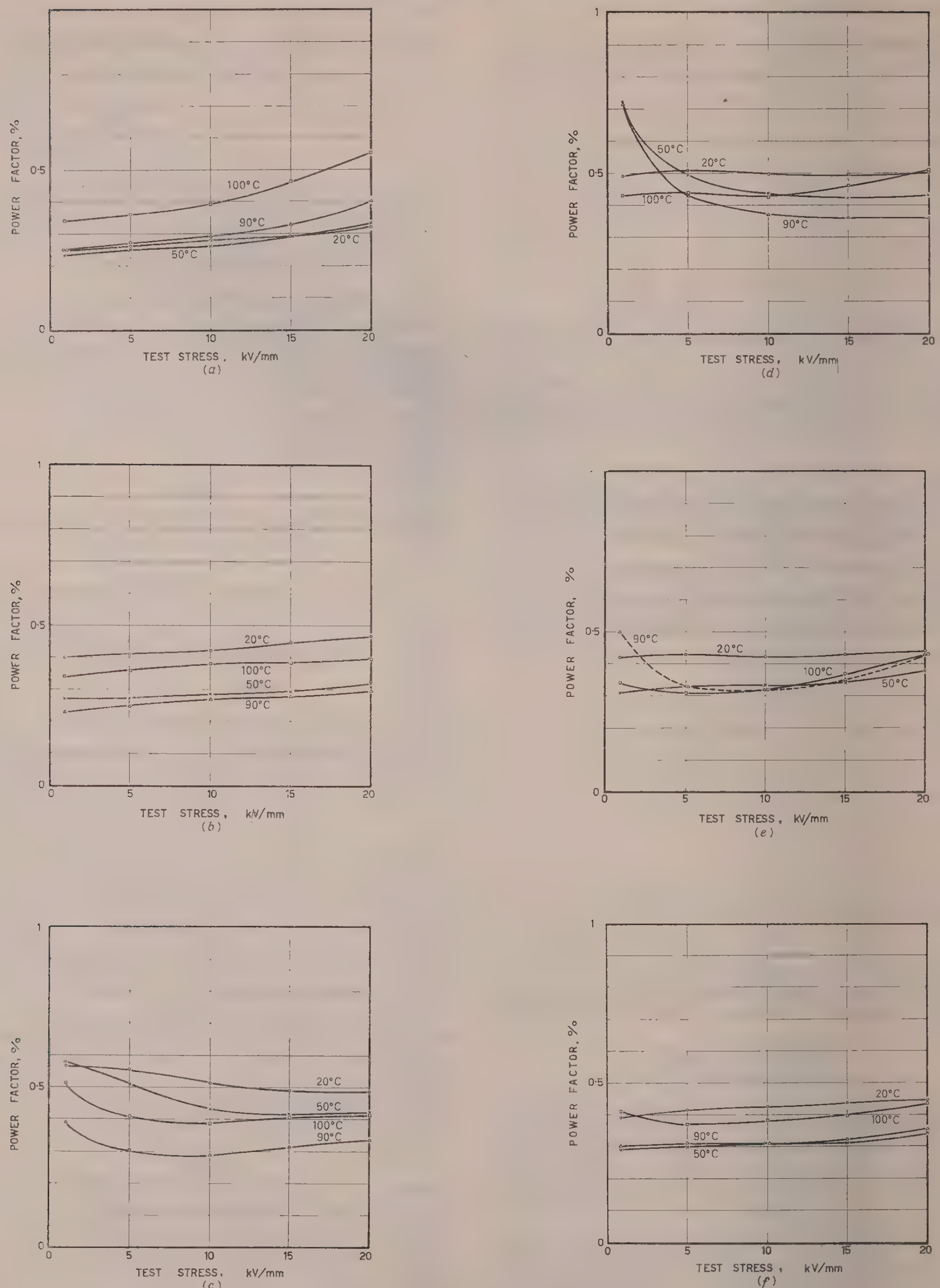


Fig. 7.—Power-factor/voltage characteristics of oil-impregnated paper aged in sealed containers in the presence of copper and in the absence of air and tested at various temperatures.

(*a*) Unaged sample.
(*b*) Aged for 800 days at 90° C.
(*c*) Aged for 550 days at 100° C.
(*d*) Aged for 240 days at 110° C.
(*e*) Aged for 120 days at 120° C.
(*f*) Aged for 60 days at 130° C.

oleate) on the power factor of cable oil. The addition of 0·02% and 0·2% copper oleate corresponds to acidity values lower than 0·03 mg KOH/g. Such amount of acid, which is detected with great uncertainty by ordinary means, can certainly be present in new cable oils which show, on the other hand, quite satisfactory power factors (see Table 5).

In addition to small traces of acid, the oil used for the test, which is a standard cable oil, also contained an amount of peroxides corresponding to 0·0116 g of active oxygen per 100 g of oil. Such a small amount can be responsible for the presence of copper ions in a dangerous proportion, according to some authors.[15]

The above statement has been confirmed by carrying out comparative tests in which a copper passivator (0·05% di-salicylidene-ethylenediamine) was added to the cable oil. The power factor of the oil with passivator added did not show any change after heating in the presence of copper, as in the case of the tests carried out in the absence of copper.

(3.1.3.5) *Tests on Cable Oil in the presence of Tinned Copper.*

Cable oil heated in the presence of tinned copper and in the absence of air for four days at 140° C showed no variation in acidity and a very slight increase in power factor (see Table 6). In other similar tests cracks occurred in the tin surface during heating, and in such cases the power factor of the oil increased by the same amount as in the case of plain copper.

(3.1.3.6) *Tests on Cable Oil in the presence of Aluminium.*

Cable oil heated in the presence of aluminium and in the absence of air for four days at 140° C did not show any variation, either in acidity or power factor (see Table 6).

(3.1.3.7) *Tests on Impregnated Paper in the presence of Copper, Tinned Copper and Aluminium.*

The effect of heating on impregnated paper in the presence of metals and in the absence of air was investigated by testing separately variation of the mechanical strength of paper, variation of the acidity and power factor of oil, and variation of power-factor/voltage curves of the impregnated paper measured at different temperatures on plane capacitors.

In Fig. 7 the most important and typical results of a lengthy series of comparative tests on impregnated paper are summarized after ageing at 90, 100, 110, 120 and 130° C for different periods of time. Fig. 8 shows the variation of oil acidity, oil power factor and paper folding strength taken from the same samples.

The following conclusions can be drawn from the curves of Figs. 7 and 8 and from other data not shown:

(*a*) The thermal deterioration of paper is the same as that observed in the tests carried out on paper alone and on impregnated paper without metals (Sections 3.1.3.2 and 3.1.3.3).

(*b*) The increase of oil acidity is the same as that observed in the tests carried out on impregnated paper without metals (Section 3.1.3.3).

(*c*) The presence of copper increases the power factor of oil.

(*d*) The power factors measured against voltage at different temperatures on plane capacitors composed of impregnated paper aged in the presence of copper indicate only a moderate increase if compared with those measured on capacitors composed of impregnated paper not submitted to ageing. The power-factor curves show, however, even for the less severe treatment, the trend to assume the characteristic shape which is typical of cables after many years of operation.[19,20] This particular behaviour consists in the tendency for the 'power-factor difference' to become negative whilst it is generally positive in the case of new cables. Moreover, even for the less severe ageing, an inversion is observed of the relative positions of the power-factor curves measured at various temperatures compared with those measured on unaged dielectrics. In fact, for aged dielectrics the power-factor curves corresponding to the lowest temperature are very often at a higher level than the curves corresponding to the higher temperature.*

(*e*) With regard to the shape or relative positions of power-factor curves, the results obtained on plane capacitors made with impregnated paper in the presence of copper are very similar to those found after the same ageing (120 days at 120° C) on capacitors made with

(i) Impregnated paper in the presence of copper wire and copper passivator.
(ii) Impregnated paper in the presence of tinned copper wire.
(iii) Impregnated paper in the presence of aluminium wire.
(iv) Impregnated paper alone.

The general conclusion is that the metals which are generally present in oil-filled cables seem to have little practical influence

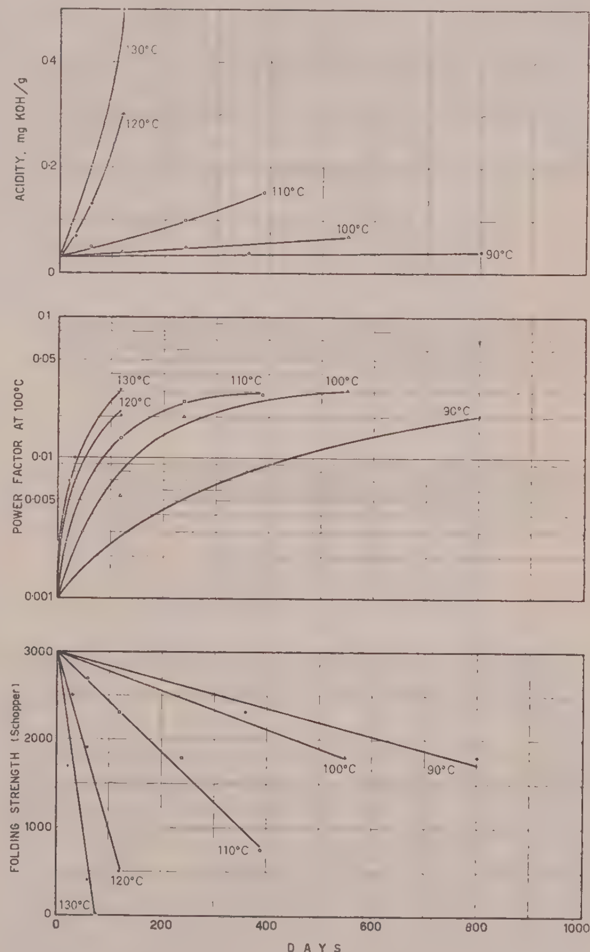


Fig. 8.—Variation of oil acidity, oil power factor and Schopper folding strength of oil-impregnated paper aged in sealed containers in the presence of copper and in the absence of air.

* These phenomena can be explained by the presence of very small particles produced by the deterioration of the paper in suspension in the oil. With reference to the phenomenon of negative power-factor difference the absolute value of the dielectric losses due to particle movement varies very little with the applied voltage if these particles have such dimensions and electrical charges as to reach, under the electric field, their maximum displacement at low stress. If, therefore, the dielectric losses remain almost constant, the power factor decreases with increasing voltage since $\tan\delta = \frac{\text{Dielectric losses}}{\omega C V^2}$. With particular reference to the phenomenon of inversion of the relative positions of power-factor curves, the losses due to the movement of the particles in suspension in the oil reach a maximum value which depends on their size and on the viscosity of the oil. If the particles have such dimensions as to determine the maximum of the losses at a viscosity corresponding to room temperature, the power factor at this temperature can be higher than that measured at the higher temperatures.

on the variation of the power factor of the dielectric as a consequence of thermal ageing and that this variation can be ascribed for the most part to the deterioration of the paper.

(3.2) Combined Effect of Temperature and Electric Stress

The investigation to determine the combined effect of temperature and electric stress was carried out on cable models consisting of plane and cylindrical capacitors and on experimental cables.

(3.2.1) Tests on Cable Models.

(3.2.1.1) *Description of Tests.*

Four tests on plane and two on cylindrical capacitors were carried out.

The cable models, both plane and cylindrical capacitors, are of the type described in a previous paper.[16]

The plane capacitors used for these tests have a disposition of the perforated paper discs simulating the 50/50 registration in the cable. Two of these capacitors have a corrugated electrode corresponding to a stranded conductor having 2 mm diameter wires. In these capacitors [Fig. 9(*b*)] the paper discs

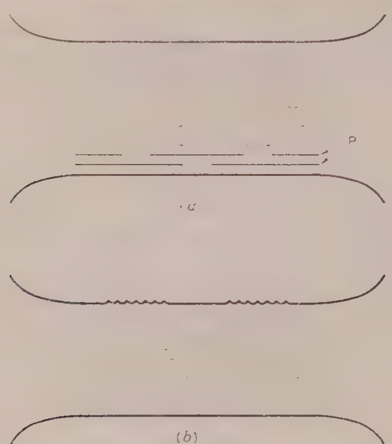


Fig. 9.—Schematic representation of cable models (50/50 registration).

(*a*) Metal electrode screened with carbon-black paper, P.
(*b*) Corrugated electrode, first insulating paper adjacent to corrugated electrode overlapped.

adjacent to the corrugated electrode reproduce the condition of a cable in which the first tape is applied with overlapping against the conductor. The two other capacitors [Fig. 9(*a*)] have a carbon-black-paper screening against one electrode. The thickness of the insulation is about 0·8 mm.

The cylindrical capacitors have the inner electrode made of a 20 mm diameter brass tube, screened with two carbon-black-paper tapes 0·14 mm thick. The insulation is made of several paper tapes 0·08 mm thick and 20 mm wide, of the type used for the plane capacitors, applied with 50/50 registration to a total thickness of 1 mm. The outer electrode is a 0·8 mm tinned-copper wire closely wound on the outside of the insulation.

The capacitors were kept at a mean temperature of 120° C (minimum 115° C, maximum 125° C). The plane capacitors were steam-heated. The cylindrical capacitors were heated by oil circulating in the inner conductor. During the test period a voltage of 11 kV, corresponding to a stress of 13·5 kV/mm, was continuously applied to the plane capacitors with corrugated electrodes, and a voltage of 13 kV, corresponding to a stress of about 16 kV/mm, to the plane capacitors with electrode screened with carbon-black paper. A maximum stress of about 16 kV/mm was applied to the cylindrical capacitors. Power factor tests and check tests at a voltage 10% lower than the expected discharge inception voltage were carried out every 15 days during the test period, which lasted from a minimum of 400 days to a maximum of more than 4 years.

(3.2.1.2) *Results of Tests on Cable Models.*

At the end of the tests some of the capacitors were submitted to breakdown test using alternating current or impulse, and some to visual examination and inspection of the characteristics of oil and paper. A summary of the results is shown in Table 8. Although only a few tests were carried out and two of them had to be discontinued owing to a fault in the temperature-control system, the results obtained are significant and indicate the following conclusions:

(*a*) In spite of the severe thermal and electric treatment, the electric strength both with alternating current and impulse was unaffected.

The mechanical deterioration of the paper at the end of the tests was so serious that, except in one case, the determination of the folding strength was impossible owing to the extreme brittleness of the paper. It was, on the other hand, confirmed that the paper, in spite of the severe mechanical deterioration, retained its original impermeability.

(*b*) The power-factor was increased by 20–40% in the case of the capacitors without carbon-black-paper screening (2 tests), whilst it remained unchanged in the case of carbon-black-paper screening (4 tests).

(*c*) The use of unscreened conductors seems to be inadvisable at elevated stress and temperature (incipient carbonization showed on the paper adjacent to the corrugated electrode).

It appears that in the case of conductors screened with carbon-black paper, maximum electric stresses and temperatures as high as 16 kV/mm and 120° C respectively could be allowed.

(3.2.2) Tests on Experimental Cables.

(3.2.2.1) *Description of Tests.*

The tests, which are still running, are carried out on oil-filled 50 kV cables with a single core, 0·1 in², 15·2 mm diameter. Some of the cables have carbon-black-paper screening on the conductor and over the insulation (the carbon-black paper over the insulation is interleaved with a metallized-paper tape). Some have no screening on the conductor and a metallized paper interleaved with an insulating paper over the insulation.

The total insulation thickness is in both cases 5 mm and is composed of insulating paper tapes 0·08 and 0·11 mm thick and 20 mm wide and carbon-black paper, when present. Two types of tests are running:

(*a*) Continuous heating at 120° C uniform through the dielectric, obtained by a steam jacket on the outside of the cable. A voltage of 40 kV, corresponding to a maximum stress of 10 kV/mm is applied continuously.

(*b*) Load cycle tests of 48 hours consisting of 24 hours heating up to 120° C and 24 hours without heating; a voltage of 40 kV is applied continuously. The time necessary to reach 120° C is about 3 hours. To evaluate the combined effect of temperature and electric stress, power-factor tests are carried out daily at 120° C at 20, 40 and 80 kV.

(3.2.2.2) *Results of the Tests.*

The results of the tests are shown in Figs. 10 and 11 and can be summarized as follows:

(*a*) In the case of continuous heating, the power-factor difference between 20 and 80 kV measured at 120° C on the cable with unscreened conductor became negative after about 20 days of tests. The power factor measured at 40 kV and at 120° C increased by about 18% after 120 days. These results are in agreement with those obtained on cable models.

(*b*) In the case of continuous heating, the power-factor difference of the cable with carbon-black-paper screening, which is much higher at the beginning of the test, became practically zero after 90 days. The power factor measured at 120° C and 40 kV decreased from 0·0041 to 0·0036 (12%) after 120 days, confirming the

Table 8

SUMMARY OF TESTS CARRIED OUT ON CABLE MODELS AFTER HEATING AT 120° C WITH VOLTAGE APPLIED

Type of capacitor	Duration of test	Stress applied during test (max)	Power factor at 120° C		Breakdown stress (max) at the end of the test		Number of folds to fracture	Remarks
			Initial	Final	Impulse	Alternating		
	days	kV/mm	%	%	kV/mm	kV/mm		
Plane; corrugated electrode (a)	570	13·3	1·3	1·55	—	—	160 (b) (30 — 280)	Blackening and carbonization on the first paper against grooved electrode was observed. (a) The temperature rose to 160° C after 320 days for about 5 hours owing to a fault in the temperature-control system at night (b) The same paper before test gave number of folds to fracture 4 500
Plane; corrugated electrode (a)	1 510	14·3	1·09	1·56	88·2 (b)	—	(c)	(a) The temperature has risen to 160° C after 320 days for about 5 hours due to a fault in the temperature-control system at night (b) The breakdown stress of similar capacitor (not submitted to test at 120° C) is 90 kV/mm (mean value), dispersion range 83·3 — 98·6 kV/mm. Porosity of paper 2·8 × 10^6 (E.U.) not changed after test at 120° C (c) Too brittle to be tested
Plane; carbon-black paper screening	420	15·7	0·88	0·67	—	—	(a)	Test discontinued after breakdown owing to rise of temperature to 250° C during 10 hours (a) Too brittle to be tested
Plane; carbon-black paper screening	915	15·1	0·74	0·76	93·3 (a)	—	(b)	(a) The breakdown stress of similar capacitor (not submitted to test at 120° C) is 95 kV/mm (mean value), dispersion range 89 — 99·5 kV/mm. Porosity of paper 2·8 × 10^6 (E.U.) not changed after test at 120° C (b) Too brittle to be tested
Cylindrical; carbon-black paper screening	560	16	1·28	1·3	—	—	(a)	Test discontinued after 560 hours owing to rise of temperature to 200° C and reduction of the ionization inception voltage to a value lower than the test voltage due to gas evolution (a) Too brittle to be tested
Cylindrical; carbon-black paper screening	400	16·1	0·5	0·55	—	48·3 (b)	(a)	Carbonization observed on the first paper against the outer electrode (fine copper wire) (a) Too brittle to be tested (b) The breakdown stress of similar capacitor not submitted to test at 120° C varies from 45 to 50 kV/mm

The paper used for both plane and cylindrical capacitors was 0·08 mm thick, impermeability 2·8 × 10^6 E.U.

behaviour observed on cable models with carbon-black-paper screening.

(*c*) In the case of load cycling, the cable with unscreened conductor also showed a negative power-factor difference. The power factor measured at 120° C and 40 kV increased from 0·004 to 0·0052, i.e. by 30%, a value which is in good agreement with the results obtained on cable models.

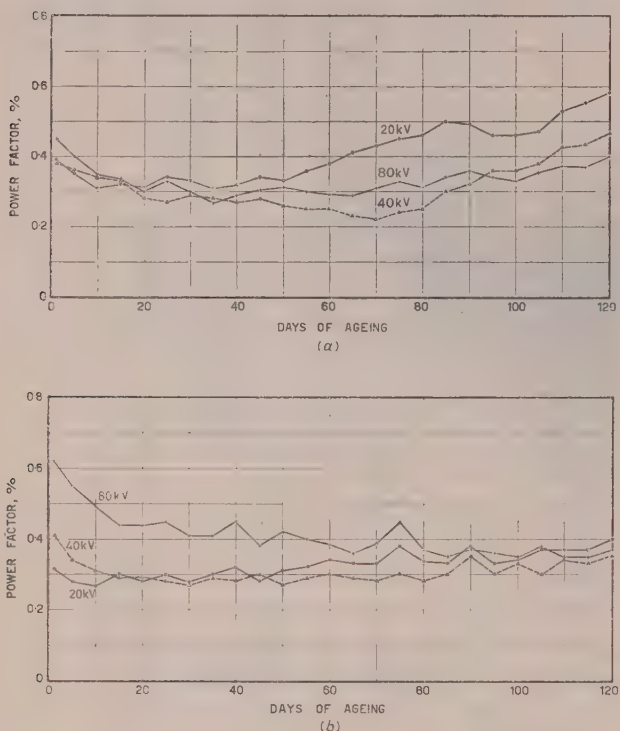


Fig. 10.—Effect of continuous application of temperature (120° C) and voltage (40 kV) on power-factor/voltage characteristics of a 50 kV oil-filled cable.

(*a*) Unscreened conductor.
(*b*) Carbon-black paper screening of conductor and insulation.

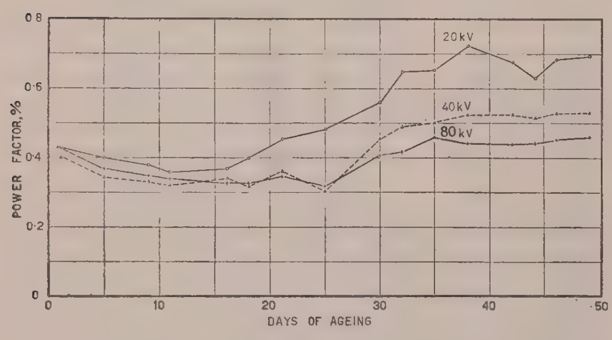


Fig. 11.—Effect of heat cycling up to 120° C and continuous application of voltage (40 kV) on power-factor/voltage characteristic of a 50 kV oil-filled cable.

(4) DISCUSSION

The results of the investigation can be briefly summarized as follows:

(*a*) The paper is the component most affected by temperature.

(*b*) In the range of temperature and duration considered, the electric strength is not practically influenced by the combined action of temperature and electric stress. A temperature as high as 120° C seems to be permissible for several months.* Maximum operating stresses of the order of 16 kV/mm appear to be allowable in low-pressure oil-filled cables in conjunction with such temperatures.

(*c*) The power-factor increase is moderate and does not seem to be proportional to time or temperature.

(*d*) The mechanical characteristics of paper tapes taken from cables after more than 20 years of operation are still quite good. It appears, therefore, that such cables have certainly been operated at a much lower load than the rated one and that if the future load rating is the same they will go on operating satisfactorily for a further long period.

The question then arises: what would have been the more convenient utilization of the cables, or for how many years will they go on operating satisfactorily if the present load is maintained?

A reply to this question is possible if the mechanical deterioration of paper is taken as the criterion. In fact the paper is the element which plays the most important part in this problem. It is, however, necessary to establish the limit of deterioration of the paper which should not be exceeded.

Laboratory tests on both cables and models, in which the insulation was not submitted to movement during testing, made it evident that severely deteriorated papers (number of double folds to fracture, 100 or less) maintain their impermeability and electric strength unchanged.

It is most probable that, in the case of cables buried directly in the ground, the same degree of deterioration could be allowed because any movement is prevented. In the case of cables which are free to move as a consequence of expansion and contraction (cables laid in ducts or troughs, etc.) the situation is quite different and less definite. In such cases an upper limit to the amount of deterioration of the paper has to be fixed in order that the cable can bend during the imposed load cycling without tearing the paper tapes. Buried cables appear, therefore, to have a certain superiority compared with cables laid under different conditions. Practical tests to determine the ultimate limit of allowable mechanical decay for such cables are being made.

Considering now the question of allowable normal and emergency loadings, curves of the type of Figs. 4 and 5 provide interesting indications.

They offer the possibility of determining the equivalence between overloads of limited duration and the normal load. They can also be employed to evaluate the condition of a dielectric which has been submitted at various times to different temperatures for varying periods, or to decide the permissible normal and emergency loadings for a given cable in relation to its desired life and the desired reliability of the service. In fact, the additive property of the effects is generally admitted for phenomena of this nature, and tests carried out by the authors and previous tests carried out elsewhere[9] have confirmed the effects of intermittent heating at high temperature to be additive.

From the curves of Fig. 2, other curves can be deduced for temperatures lower than 90° C using the 'temperature rule', which is that a decrease of 10° C in the ageing temperature extends by a factor of 2–2·5 the time required to reach the same deterioration. This factor of 2–2·5 has been confirmed in tests carried out in other laboratories.[9, 17] For this purpose the curves of Fig. 12 have been calculated by extrapolation of the data obtained in the test carried out at 120° C according to the 'ten degrees' rule using a factor of 2·2. These curves show the time required to reduce the original folding strength of paper to various percentages of the original values as a function of time of ageing at various temperatures.

* Tests completed when the preparation of the present paper was already finished have shown that the impregnated paper submitted to severe ageing beyond the limit corresponding to the complete loss of all mechanical strength, at a certain moment, undergoes a further very quick chemical decay. This decay is characterized by a large formation of water (up to 5% of the paper weight) and CO_2. The phenomenon has been observed after about 30 months of continuous ageing at 120° C or after about 15 months of continuous ageing at 130° C.

As an example, cables D and E can be considered, for which the folding strength of the paper adjacent to the conductor indicates a slight deterioration. Unfortunately the original characteristics of the papers used for the manufacture of these cables are not known. Supposing, however, that they were similar to those of the cable paper considered in Section 3.1.1, it could be deduced from the data of the curves of Fig. 12 that

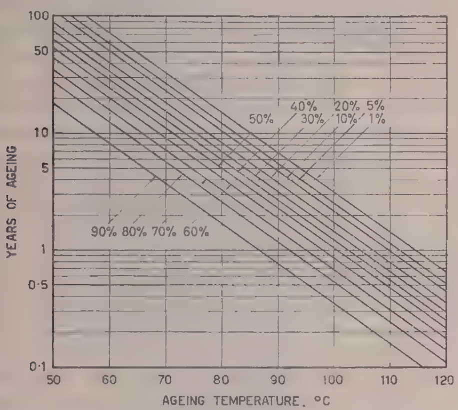


Fig. 12.—Time required to reduce the folding strength of cable paper to various percentages of the original value as a function of temperature.

the equivalent mean temperatures for cables D and E were 60° and 55° C respectively. In addition, it could be seen that, if the same load is maintained in the future, the paper tapes near the conductor will reach a folding strength of 100 folds to fracture (0·033 of the original value) in 60 and 90 years respectively.

It is interesting to note the peculiar coincidence between the value of 55° C of the equivalent mean temperature for cable E (225 kV, laid in Paris) deduced from the curves of Fig. 12 taking into account the state of cable paper and the calculated value of 50° C obtained by integration of the curve of Fig. 2 based on the maximum monthly load peaks recorded during the period March, 1946 to August, 1955.

In conclusion, it seems possible, using curves of the type of Fig. 12, not only to judge the actual condition of a cable which has been in operation for some years, but also to plan, for old as well as for new cables, the most convenient temperatures for normal emergency loadings, and their duration and frequency in relation to the desired life.

The authors hope that the foregoing analysis of the factors involved in the ageing of the oil-filled cable dielectric may serve as a basis for future improvements.

(5) ACKNOWLEDGMENTS

The authors recall that this investigation was sponsored by the late Dr. L. Emanueli, who followed its development with great interest and provided useful suggestions and helpful criticisms, and they wish to pay here a tribute to his memory.

Acknowledgment is made to Electricité de France for the noteworthy contribution to this investigation in supplying samples of cables taken from lines in full operation, purely for testing purposes.

The authors' thanks are due to Pirelli S.p.A. for permission to publish the paper.

(6) REFERENCES

(1) Clark, W. S.: 'Notes on the Effect of Heat on Impregnated Paper from Cable Insulation', *Transactions of the American I.E.E.*, 1921, **40**, p. 137.

(2) Fisher, H. W., and Atkinson, R. W.: 'The Effect of Heat on Paper Insulation', *ibid.*, p. 143.

(3) Del Mar, W. A.: 'The Maximum Safe Operating Temperature of Low-Voltage Paper-Insulated Cables', *ibid.*, p. 97.

(4) Torchio, P.: 'Permissible Operating Temperatures of Impregnated Paper Insulation on which Dielectric Stress is Low', *ibid.*, p. 107.

(5) 'Deterioration of Impregnated Cable Paper Subjected to temperature only', *Journal of the American I.E.E.*, 1925, **44**, p. 508.

(6) Clark, F. M.: 'Pyrochemical Behavior of Cellulose Insulation', *Transactions of the American I.E.E.*, 1935, **54**, p. 1088.

(7) Halperin, H.: 'Load Rating of Cables', *ibid.*, 1939, **58**, p. 535 and 1942, **61**, p. 930.

(8) Clark, F. M.: 'Factors Influencing the Mechanical Strength of Cellulose Insulation', *ibid.*, 1941, **60**, p. 778.

(9) Clark, F. M.: 'Factors Affecting the Mechanical Deterioration of Cellulose Insulation', *ibid.*, 1942, **61**, p. 742.

(10) Clark, F. M.: 'Chemical Changes Affecting the Stability of Cellulose Insulation', *Transactions of the Electrochemical Society*, 1943, **83**, p. 143.

(11) Malmlöw, G.: 'Thermal Ageing Properties of Cellulose Insulation Materials', *Acta Polytechnica*, 31 (1949), Electrical Engineering Series, **2**, No. 1.

(12) Fabre, M. J.: 'Les critères chimiques de dégradation du papier imprégné d'huile dans les appareils électriques', *Revue Générale de l'Electricité*, 1957, **66**, p. 17.

(13) Staudinger, H., and Jurish, I.: 'Über der Abbau von Cellulose durch Oxydationsmittel', *Papier-Fabrikart*, 1937, **49**, p. 462.

(14) Stamm, A. J.: 'Thermal Degradation of Wood and Cellulose', *Industrial and Engineering Chemistry*, 1956, **48**, p. 413.

(15) Feich, G., Olds, W. F., and Eich, E. D.: 'The Chemistry of Cable Oil Deterioration', *Insulation*, June, 1959, p. 19.

(16) Gazzana-Priaroggia, P., and Palandri, G.: 'Research on the Electric Breakdown of Fully Impregnated Paper Insulation for High Voltage Cables', *Transactions of the American I.E.E.*, 1955, **74**, Part III, p. 1343.

(17) Fabre, W. J.: 'Les lois de dégradation du papier imprégné d'huile dans les transformateurs', *Bulletin de la Société Française des Electriciens*, 1959, **9**, 7th Series, p. 409.

(18) Wyatt, K. S.: 'Deterioration of Insulating Oil through Interaction with Cable Metals', C.I.G.R.É., Paris, 1937, Paper No. 233.

(19) Garton, C. G.: 'Dielectric Loss in Thin Films of Insulating Liquids', *Journal I.E.E.*, 1941, **88**, Part II, p. 103.

(20) Tinel, G.: 'Régénération de l'huile d'un câble à haute tension système Pirelli', *Bulletin de la Société Française des Electriciens*, 1954, **4**, 7th Series, p. 552.

(21) Salomon, T.: 'Quelques observations récentes sur les modifications subies par les huiles pour câbles Pirelli au cours de leur service', *ibid.*, p. 557.

[The discussion on the above paper will be found on the next page.]

DISCUSSION ON THE ABOVE TWO PAPERS

Before the Supply Section 19*th April, and the* Southern Centre *at* Brighton 17*th April*, 1961.

Mr. S. E. Goodall: The two papers are complementary and set out clearly to demonstrate the excellent practical performance that oil-filled cables have achieved and the continuing success and development which are attending the further work in this field.

With regard to the paper by Dr. Gazzana-Priaroggia *et al.*, cable makers and users of cables are always seeking a sensible way of assessing the possible useful age which should be ascribed to cables, especially in the e.h.v. range. This, of course, is a most difficult matter, because until the years have passed and something untoward has happened it is not possible to be sure. The paper brings us a notable step forward in the direction of assessing beforehand what the likely life is supposed to be.

One matter brought out in the paper is the vitally important factor of the mechanical deterioration of the paper itself.

If we attempt to apply Fig. 12 in practice we very soon run into difficulty. For example, I deduce that at 85° C the mechanical strength of the paper, judged by the deterioration of the folding property which the authors use as a method of assessment, is reduced to 1% in less than 10 years. It is stated in Section 4 that the object of the experiment is to attempt to use these curves as an actual method of assessing when the cable is likely to be unreliable. It is not stated clearly at which percentage of deterioration one is to draw the line and regard the cable as useless.

One useful fact which the authors bring out is that we may expect the life of a cable to be considerably enhanced if it is buried directly in the ground. In other words, if constant movement is permitted in troughs or ducts this will contribute to the deterioration of the paper. I must, however, give a word of warning, because, although a cable may be buried in the ground, it is not buried for its full length. It has to come out somewhere, and there may be movements at the ends. We have, therefore, to be cautious in assuming that if we bury cable in the ground it will go on for ever, whereas if we put it in a trough it will not.

Other factors to be considered in dealing with this vexed question of assessing overall life are the variations of normal load, load cycles, etc., and more particularly variations during life of soil resistivity. We do not know enough about this subject, but fortunately a programme has been launched and a mass of results already obtained by collaboration between the E.R.A. and the Area Boards in the form of an *ad hoc* committee under the chairmanship of Mr. Welch, the Chief Engineer of the London Board. In due course this work should prove to be extremely valuable.

The paper by Dr. Arman *et al.* points out, quite properly, that a useful increase in impulse strength has been obtained by using high-impermeability paper, but Section 2.3.2 seems to imply that further advantages can be obtained by using still higher levels of impermeability, which can be produced by new impregnating techniques. According to the experimental data which we have obtained this is not likely to be the case; in fact, we have found that excessive impermeability and density are to be avoided because they lead to increase in power factor.

In Section 2.1.2 I am worried by the power factor quoted for the oil, particularly if it is measured at the usual stress level of 5–10 kV/cm, because this does not represent the normal standard of oil used in cable production. It is very important that power-factor data relating to oil should not be quoted without stating the stress at which the measurement is made.

Section 2.2.1 bothers me a little, because of the authors' emphasis on the use of carbon-black paper as screening for the conductor. It seems that the authors are emphasizing all the time the desirability of increasing the a.c. strength. I agree that it is a very good scheme after type-testing by impulse to ensure that, in fact, there has been no incipient breakdown by applying considerable alternating over-voltage, but I cannot see much virtue in applying too high a voltage for that purpose. They recommend, with some caution, $2\frac{1}{2}$ times the working voltage. Since the operating stress and the maximum stress of the conductor at working voltage differ greatly for different voltages over the whole range of cable design up to 275 kV, it would seem much more sensible to suggest a range of over-voltage factors, such as $3\frac{1}{2}$ to 2.

Mr. G. S. Buckingham: The operational experience of these cables is extremely high. I recently visited the Hell Gate power station in New York, which had its first 132 kV cable laid from it in 1925. The cable is still working in an eminently satisfactory manner. The engineers said that they had had a drum of cable which was intended as a spare, but as they had never used it in 35 years they got rid of it a little while ago and now have no spares. The authors must be congratulated on being the first to submit a 400 kV cable to the very rigorous type-approval tests which are now applied in this country.

It is clear from Fig. 2 of the paper by Dr. Gazzana-Priaroggia *et al.* that the 225 kV cables in Paris have never been properly warmed up. The authors are trying to tell us that we can use these cables with conductor temperatures up to 110° C, but this is not done because we do not know the temperature of the conductors. A most important requirement is therefore some simple device to determine these temperatures, since we now have very little means of doing this while the cables are on load. The thermal resistivity of the soil changes, the loads are cyclic and vary, and in an emergency it is difficult to make any assessment of overload capacity. If the authors could produce some thermal image of what is going on inside the cable, it would be a most valuable contribution to our knowledge. In New York some oil-filled cables use forced circulation of the oil down the hollow core of the conductor. When it comes out this oil is warm, and by measuring the temperature it might be possible to determine the rise in temperature of the conductor through which the oil is passing.

I agree with the proposal in the paper by Dr. Arman *et al.* to use an aluminium sheath. This has many advantages over the reinforced lead sheath, but it has, of course, one serious disadvantage, namely the corrosive effect of the soil on aluminium. The authors are a little too complacent about the anti-corrosive finish which they propose to apply to these cables. Experience in testing anti-corrosive finishes on e.h.v. cables in this country indicates that they are easily susceptible to damage from external causes. With aluminium sheaths the integrity of the whole cable may depend on the integrity of the anti-corrosive finish. Fig. 12 of the paper by Dr. Gazzana-Priaroggia *et al.* shows that if the temperature of the cable conductors does not rise much above 60° C we get a life of 100 years, which is what I have asked for before. However, I am not sure that we shall get 100 years' life from the aluminium sheath protected in the manner proposed by the authors.

Dr. A. L. Williams: The paper by Dr. Gazzana-Priaroggia *et al.* fully describes one of the consequences of cable ageing, but the authors have not dealt with the full mechanism of ageing. Although thermal embrittlement of the paper is the most obvious consequence, it would be expected to have less influence on the characteristics of the cable than would changes

in the oil caused by the combined effect of temperature and stress in the presence of residual air and moisture. Whatever precautions are taken during manufacture, installation and service, these contaminants are always present to some degree and they can cause a progressive increase in power factor, which is particularly important in very-high-voltage cables. Would the authors express an opinion, for example, on the percentage of moisture which can be tolerated in a dielectric working at 16 kV/mm at 120° C, and would they elaborate on the statement made in Section 2.1 that 'significant' information was obtained from the oil taken from the Paris cable?

The power-factor/stress phenomenon which results from the use of a carbon-paper conductor screen is extremely interesting. Although it disappears after a few heat cycles and is, in itself, apparently harmless, it is objectionable because it could conceal defects which are less harmless. As one example, a similar but smaller power-factor/stress increase is caused by the omission of a dielectric screen (or by gross defects in a dielectric screen), and this can result in carbonization of the oil at high stresses, as shown in Table 1 of the paper. Although the technical merit of a carbon-paper conductor screen, by comparison with other constructions, is debatable, carbon paper has the great advantage of relative cheapness. A knowledge of the cause of the phenomenon may indicate some way of avoiding it. Can the authors suggest an explanation?

Mr. R. S. Orchard: Can Dr. Arman *et al.* state whether tank impregnation is likely to be developed for use with aluminium-sheathed as well as lead-sheathed cables?

The authors suggest that a second type test—a 24-hour voltage type test—should be used as a check to see whether the impulse test has been passed successfully. This is surely a complication which is not justified; every type test should stand on its own, and methods should be developed for detecting any fault within that test.

Referring to high-temperature operation, the authors suggest that trouble may be caused if a temperature of 100° C is exceeded for lead sheaths. Elsewhere it has been proposed that a figure of 260° C should be used as the maximum lead-sheath design temperature under short-circuit short-time conditions. More information to obtain some relation between these two figures would be useful.

In Section 5·7 the authors suggest that a figure of 110° C might be used for limited periods. We should surely be unwise to design h.v. oil-filled cable systems on this basis until we have far more information than has been made available up to the present.

Further information on the authors' proposals to surround cables with a weak mixture of cement and sand to prevent soil drying out at high temperatures and more details of the effect on the life of cables by operating them at higher temperatures would be useful. Could not a Code of Practice on the overloading of cables similar to that already available for transformers be prepared?

Mr. J. Banks: Taken with other papers presented to The Institution in the last few years a bustling activity in the h.v. cable field since the war is indicated. It is not surprising that we have an impassioned plea in the paper by Dr. Arman *et al.* for the acceptance of the economic benefits of this development, since some people think that it has been going on much too quickly. It is surprising that in the same paper the authors hint that the type test programme, which is usually the basis of design in this country and has been for the last few years, and which has been the basis for this development, is, in fact, inadequate. They suggest an additional test—a 24-hour a.c. test.

It would be a pity if in this country, which can be said to have led the world in proposing for h.v. cable work a performance specification which gives the designer fair freedom with tests related to performance conditions, we should propose a change from this practice and the introduction of an arbitrary 24-hour test. The authors themselves are not too confident about this, because they do not wish to be dogmatic on the question of the voltage level, and that statement in itself indicates the arbitrary nature of the test. They do make the dogmatic statement that the loading-cycle test is inadequate. If it is inadequate in duration, let us consider that; but it is a test related to performance conditions, and that principle is worth keeping.

On the question of paper lapping and the need for controlled tension, a great deal has been done in recent years. The authors carefully refer to the control of humidity allied to the control of tension, but they do not suggest any level of humidity. As one of the basic problems of paper lapping is to avoid subsequent changes in the mechanical dimensions of the paper after lapping, I should regard it as desirable to use low humidity. Furthermore, one of the main factors in the bending of a cable is the behaviour of the conductor. One can deal in an elegant mathematical way with the lapping-tension pattern in terms of bending the insulation, but the situation is much more complicated when the conductors are considered. Large conductors need a great deal of attention.

Mr. E. H. Ball: My remarks relate to Section 3.1 of the paper by Dr. Arman *et al.*, in which the authors suggest a change of type-testing procedure, and particularly to their second suggestion of an increase in the number of impulses applied. Such a

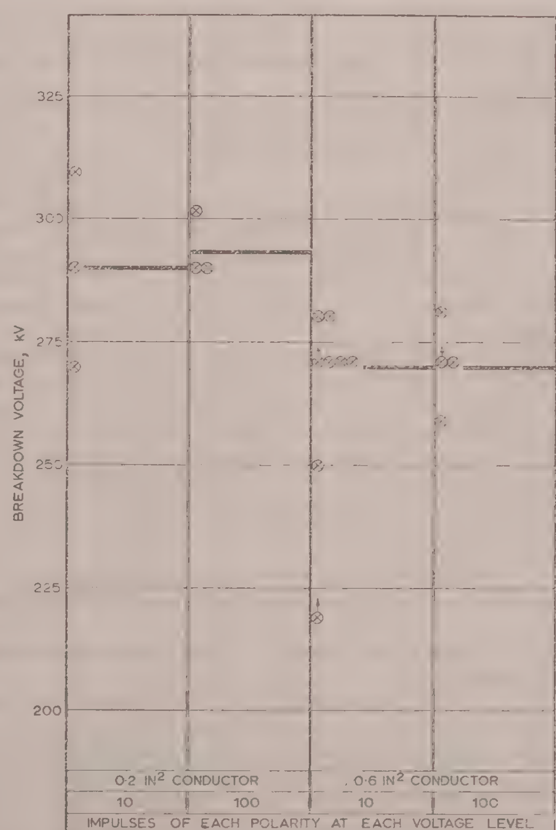


Fig. A.—Effect on impulse breakdown voltage of variation of number of impulses per voltage step for oil-filled 33 kV cable.

— Average.

⊗ Cable end failure.

change would certainly be practicable at the withstand level, although if the test were subsequently taken to breakdown the time required might become excessive.

It is of interest to consider the effect of this suggested revision to the specification, which would logically apply to all types of cable. Let us suppose that the number of impulses was increased from 10 to 100 of each polarity. Information has been published on the likely effects on solid cables, which shows that a reduction of approximately 10% in breakdown level could be expected. In the case of the oil-filled cable, there is some conflict of published evidence based on tests on capacitor samples. It may therefore be of interest to give the results of tests on actual cables, using 10 and 100 impulses of each polarity at each voltage level (see Fig. A).

The cables were factory-made 33 kV cables, of two different conductor sizes, tested in short lengths with sealing ends. The Figure shows comparative impulse test results for the two sizes separately, tested with either 10 or 100 impulses of each polarity at each voltage level. The thick lines represent average values, and it will be seen that there is no appreciable change in level with the change in number of impulses applied. There is a change in level between the two conductor sizes which is related to different stresses in the two cables.

Dr. C. H. Gosling: Mention of the d.c. characteristics of the cables would have been useful, for the d.c. transmission of energy provides an important alternative to alternating current, which has the limitation set by the losses and charging currents.

The authors have not given an explanation for the higher electric strength associated with carbon-paper screening of the conductor. It would seem possible that the carbon may absorb small bubbles of gas formed by dissociation of the oil just before breakdown.

If aluminium electrodes are used with oil as a dielectric, the breakdown strength is often less than that for copper electrodes.* I would like to know whether the authors have found a similar effect with cables.

Physical properties of the oils used have been given in both papers without including the refractive index. This constant, together with the viscosity and the specific gravity, clearly defines the chemical structure of the oil,† and thus indirectly provides information about the permittivity and gassing properties.

London has many cable routes which are laid directly in the soil, apart from short duct runs. Where these do not exceed 50 ft in length, the same-size conductor is used. A current rating is assigned which gives a conductor temperature of 85° C where laid direct, allowing for cyclic loading, thermal resistance and soil temperature. Based on previous investigations‡ the corresponding temperature in the centre of the 50 ft duct runs is about 110° C. No failure has occurred at these positions over some years of operation.

A definition of 'weak' concrete should be provided to avoid the possibility of needing pneumatic drills in order to reach the cables.

Liquid nitrogen would be safer than liquid oxygen for freezing cables on site.

I agree with the suggestion in the paper by Dr. Gazzana-Priaroggia *et al.* that particles in the oil contribute to the losses. I would go further and suggest that the alternating-voltage breakdown is brought about by these particles, either by initiating dissociation on the surfaces or by forming bridges in the butt gaps.

* Zein El-Dine, M. E., and Tropper, H.: 'The Electric Strength of Transformer Oil', *Proceedings I.E.E.*, Monograph No. 135, June, 1955 (103 C, p. 33).
† Waterman, H. I.: 'Correlation between Physical Constants and Chemical Structure' (Elsevier, 1958).
‡ Whitehead, S., and Hutchings, E. E.: 'Current Ratings of Cables for Transmission and Distribution', *Journal I.E.E.*, 1938, 83, p. 517.

Deterioration of the paper seems to begin at about 100° C. This has been found by many workers at atmospheric pressure. I have not found any reference to the deterioration at hydrostatic pressures greater than this. At atmospheric pressure the water will boil at 100° C and will pass rapidly into the oil. For higher pressures the loss of moisture would be at a much slower rate and might not show the same mechanical deterioration found at atmospheric pressure.

Mr. K. H. Tuson: Fig. 14 of the paper by Dr. Arman *et al.* is somewhat depressing to British engineers, since it indicates that apart from experimental and very short lengths no cable of over 132 kV has yet been installed in Great Britain, notwithstanding the fact that higher-voltage cables have been installed in many parts of the world going back at least 20 years. The situation may shortly alter, however, since the Chairman of the Central Electricity Generating Board has recently said that the Board are considering the use of 275 kV cables in the neighbourhood of substations to avoid the 'wirescape' effect. Furthermore, the Minister of Power has directed that a length of 275 kV transmission line shall be laid underground.

The important point is cost, and, notwithstanding the opinions of previous speakers, I regard the authors' views on overload capacity and maximum permissible temperature rise as encouraging. They will doubtless point out that they only intend their figures to relate to short-period overload capacities to match the transformers.

Perhaps they will give us their views on cross-bonding of sheaths, and also say whether there is any likelihood of 3-core cables being developed shortly for 275 kV and higher voltages.

Mr. H. Halperin (*United States*): The paper by Dr. Gazzana-Priaroggia *et al.* shows power factors of cables removed from service. We have found somewhat lower values for low-pressure oil-filled cables installed in the past 25 years. This is in accord with data on experimental cables in paper I presented to the American I.E.E. in 1942 and 1956.

As Chairman of an American group on temperature limits, I recently proposed a guide for the application of the new and higher temperatures for paper-insulated cable. Power-factor/temperature data recommended for calculating load capabilities of oil-filled cables are close to the authors' average for removed cables.

In the 1956 paper, I concluded that oil-filled cable operating at 10 lb/in^2 (gauge) could be safely designed for a maximum stress of 12 kV/mm. This was based on results of life tests on cables at maximum stresses above the 16 kV/mm used by the authors in cable model tests. Such cable might operate successfully at 16 kV/mm, but more proof than the authors' test data seems needed.

I agree with the proposed limit of 120° C, assuming that it applies (*a*) for the hottest location in a line and (*b*) for emergencies of not more than 'several months' in the cable life. Studies of results of long-term tests relating to cables (and to transformers) lead to this conclusion: As far as the thermal properties of the cable insulation itself are concerned, it would be safe to operate in emergencies at 140° C up to a total time of one month in the life of an installation.

Regarding the folding and tearing tests on paper, the former seems like too harsh a criterion for deterioration. Some cables have operated satisfactorily with almost zero folding endurance.

A graph like Fig. 12 is interesting to many users. Incidentally, it indicates a slightly lower rate of change with temperature than do the data from others.

Mr. J. A. Baskwell: One subject briefly touched on by the authors is process control of power factor. In the discussion Mr. Goodall mentions the importance of keeping down power factor in order to reduce operating costs, and Dr. Williams

emphasizes the importance of low residual moisture in the prevention of deterioration. There are many factors concerning materials used which influence power factor and power-factor difference which are controlled at early stages. After sheathing in the second vacuum process the important factors of residual moisture and gas content are controllable.

The residual water-vapour pressure is well known to be proportional to the moisture content of the paper, but methods used in the past for this determination did not differentiate between residual gas and residual moisture, which are present in variable proportions. This we can now do with a new gauge.

The valve shown in Fig. B is kept open during drying and

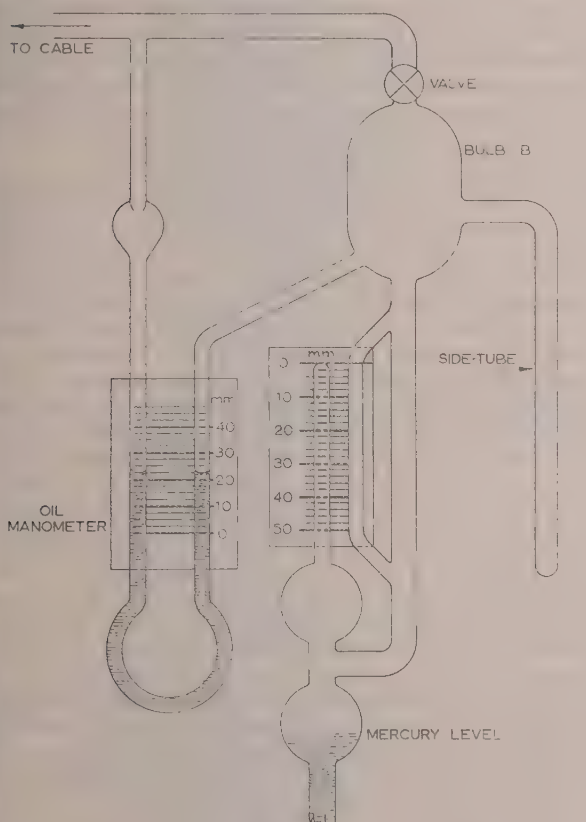


Fig. B

during shut-off tests and is closed to isolate a sample volume of the gas mixture within the cable. The side tube is immersed in a freezing mixture and in 3 min moisture is extracted from the sample volume. Then, by use of the McLeod gauge attachment the partial pressure of the residual permanent gases in the cable is measured. The oil manometer gives the water-vapour pressure.

Fig. C shows the relationship between the power factor of 3-core 132 kV cables and water-vapour pressure measured by the method described. There is some scatter due to factors other than water vapour, but the bulk of the results come in the region considered most satisfactory for process control. It is interesting that, with the method of tank impregnation referred to in the paper by Dr. Arman *et al.*, it is very easy to reduce this vapour pressure quickly to the region below 0·1 mm Hg and thus to guarantee power factor in accordance with the lower portion of the graph.

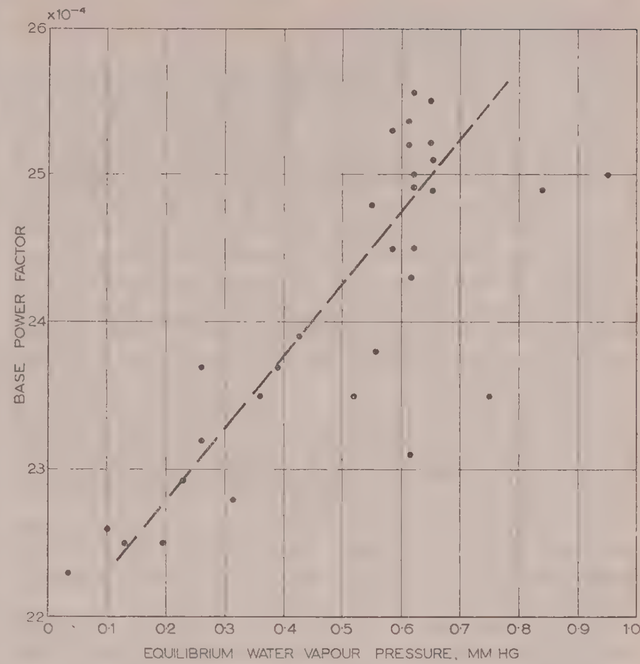


Fig. C

Mr. D. J. Skipper: The paper by Dr. Arman *et al.* rightly emphasizes the importance of adopting even higher working stresses. This is undoubtedly justified for cables operating at voltages up to and including 275 kV, but at voltages of 400 kV and above I would question whether the case for higher working stresses is so evident as the authors imply in the penultimate paragraph of Section 7.

At 400 kV the dielectric losses in oil-filled cable dielectric are of the same order of magnitude as the copper losses and are sufficient to cause a reduction in current rating of between 10 and 20%. Therefore, the dielectric losses add considerably both to the annual loss charges and also to the initial cost per MVA of useful power transmitted, and to an increasing extent as the design stress is raised. Thus, in advancing the design stress of 400 kV oil-filled cable, a point is reached where the saving in costs of materials is more than offset by the increasingly detrimental effects of dielectric losses. Judged on the basis of total annual charge the optimum design stress for 400 kV cables appears to be in the region of 180 kV/cm. For a system impulse level of 1·4 MV this is a value of design stress which should be achievable as a result of recent advances in dielectric materials and processing techniques. It therefore seems that, to obtain any improvement in the economic position of 400 kV oil-filled cables, the first requirement is a significant reduction in the magnitude of the dielectric loss before any further increase in operating stress is justified. This opinion appears to be consistent with views recently advanced by the authors' Italian colleagues (Reference 20 of the paper).

At transmission voltages above 400 kV the dielectric losses in oil-filled cable dielectric are likely to be of such an order that little or no useful power can be transmitted, and the need to replace paper by a lower-loss material will become paramount. The authors refer to the work of de Vos and Vermeer[18] in this connection, and the manufacture of a 345 kV oil-filled cable employing polycarbonate tapes has recently been reported in America. On which dielectric materials do the authors consider that further development of the oil-filled cable should be based to make

possible the operation of this type of cable at the highest transmission voltages envisaged?

Mr. D. M. Cherry: Dr. Arman *et al.* lament the lack of confidence of users in highly stressed cables, and point to the economic gains that are possible. In fact, at the higher voltages the cost of the increased dielectric losses cancels other savings in cost. Moreover, the stresses employed demand a perfection of process control which leaves no margin for error. A slight crease in one stress tape is enough to cause trouble, and, particularly with carbon-black stress tapes, would be almost impossible to detect on test. Even if the cable is perfect, it can suffer damage in laying. Working stresses have increased considerably in only a few years, and there is not yet enough service experience of highly stressed cables to demonstrate that the cable factories are indeed staffed by archangels, as the requirements of these high stresses demand.

I consider that the users are taking the fullest advantage of increased stresses that is prudent in view of the small economic gain, and that attention should now be turned to the reduction of losses, and to better coverings to enable full use to be made of aluminium sheaths with confidence.

The authors now show an epoxy-resin bushing for a considerable voltage with a very thick dielectric. How do they control the stress, and how do they prove that the dielectric is free from voids?

Mr. K. Mochlinski: I will refer only to Section 5.6 of the paper by Dr. Arman *et al.* The experiments in which cables were embedded in weak concrete mixtures to alleviate thermal instability of the soil are of great interest. The E.R.A. has carried out tests on weak concrete mixtures (about 1 : 20), and the results indicate that, provided that the right kind of mixture is used the product can be obtained dense but crumbly, and it is possible to reach a thermal resistivity in the dry state as low as 90 to 100 thermal ohm-cm. The materials used and their mutual proportions are important because mixes are possible which give a thermal resistivity of over 200 thermal ohm-cm, and 'cellular' concrete in dry state can have a thermal resistivity of 500 thermal ohm-cm.

The obvious application of the method suggested by the authors would be in dry soils with high initial thermal resistivity, but in soils which offer better initial conditions the possibility should be considered of drying and shrinking occurring outside the concrete layer, the thickness of which should therefore be chosen according to the kind of soil and operating temperature.

The cost of the cement mixture should be compared with the cost of preparation of 'thermal sand', which is composed of a suitable distribution of grain sizes which permits close packing and is known to possess advantageous thermal characteristics.

The existing ratings for paper-insulated cables are such that 11 kV cables may reach external temperatures of about 50–65° C. The much higher temperatures suggested in the paper constitute a stimulating challenge to find ways of efficient heat dissipation.

Mr. W. Holdup: I wish to refer to Section 5.6 of the paper by Dr. Arman *et al.*, from which it seems that the main limitation to extended overloads taking the conductor temperature up to something like 120° C is, in the case of buried cables, the drying out of soil. Mr. Mochlinski has outlined some of the work which the E.R.A. is doing. I will show a more practical example of the use of concrete. In 1959 a length of $0{\cdot}25\,\text{in}^2$ 132 kV cable was laid under the concrete floor of a new factory extension. As can be seen from Fig. D, half of the length was buried in a cement mortar, a weak mix, and the remaining half left in a clay soil. The cable was heated by passing a current of 450 A through the sheath, and after two months, stable temperatures were reached, 78° C in the section in the cement and 110° C in the section in soil. Those temperatures remained stable for many months and the preliminary conclusion was that thermal-instability conditions were difficult to reach. That condition, however, did not remain. There was a short shut-down at the end of 1960. The current was then reapplied, and, as can be seen from the graph, the temperature of the cable in concrete reached a stable value of 78° C after a period of 40 days, whereas the section of cable buried directly in soil has not reached stability and is still increasing. It now approaches 130° C. This work indicates that there is a danger in applying extended overloads to directly buried cables, but there is an answer in the use of a controlled cable environment.

Mr. O. S. Johnson: My first point concerns the current rating of cables and the overload capacity thereof. Considerable money must be spent in installing cables in even a weak mixture of cement, and, in addition, for oil-filled cables it is necessary to install extra oil tanks to accommodate the extra oil expansion. An increase in conductor size would give the necessary additional overload capacity in the cable, and, though it might cost more, this would, in large measure, be recovered by reduction in the I^2R losses incurred throughout the life of the cable.

The paper by Dr. Gazzana-Priaroggia *et al.* is summarized in Fig. 12. Very great reliance has been placed on a so-called rule of approximately doubling the rate of reaction for every 10° C rise in temperature. This rule is used only as a rough guide for comparatively small temperature differences, and I find it very difficult to believe that it can be applied over so wide a temperature range as extrapolating from 120° C down to 50° C, which has been done in preparing Fig. 12. The authors have recognized this to some extent in the first paragraph of Section 3.1, where they say that they have some data with regard to the deterioration of paper up to 140° C but that no use has been made of it because the reaction changes between 120 and 140° C. I suggest that, in common with many other chemical reactions, there could be a similar change in the degradation process of paper between 50 and 120° C, and before Fig. 12 is used in practice at least further examination should be made of the deterioration of paper down to lower temperatures.

The moisture content of the paper examined in the deterioration tests is not stated, but there is a reference to the work of Clark[9] in America, from which it will be seen that the moisture content plays a very important part in the reaction rate. In using the data in considering the life of cable the moisture content of the cable may play a very large part and could make very large differences in Fig. 12 and in the correlation of the data given in that Figure with measurements on the paper taken from cables which have been in service.

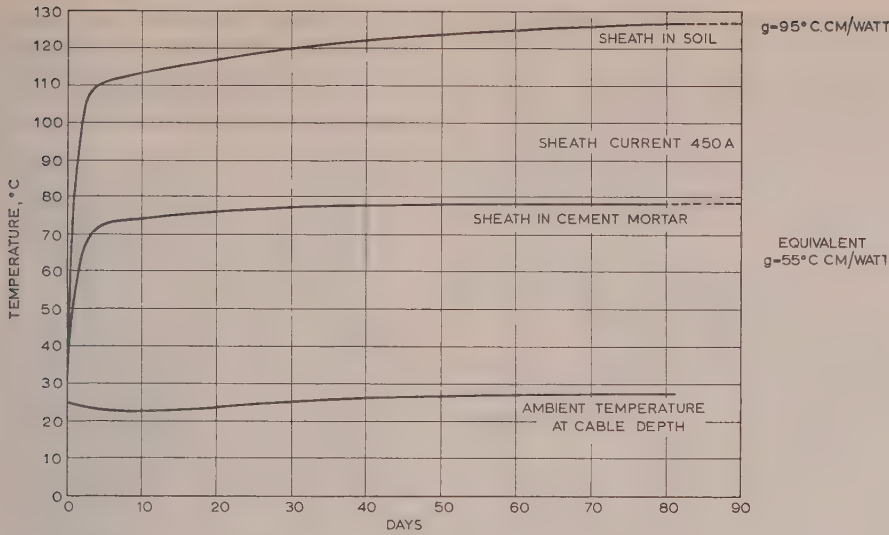
Mr. W. Holttum: My remarks apply to Section 4 of the paper by Dr. Gazzana-Priaroggia *et al.*, in which the authors mention the effect of movement due to expansion and contraction when there has been deterioration of the paper due to high-temperature operation.

Mr. Goodall states that cable buried in the ground would probably have some movement at the ends where it comes out of the ground. I agree with that and would take it further. There are primarily three methods by which the cable may be laid:

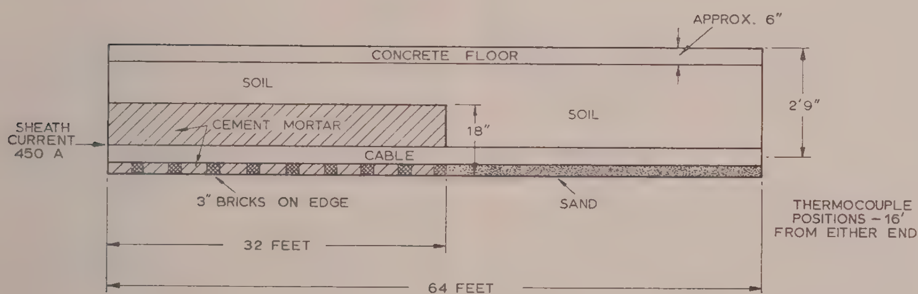
Buried directly in the ground.
Continuously supported, as in ducts or troughs.
Spaced supports, with the cable hanging freely between.

In the second case there may be less movement at the ends than in the first, but there will be localized and possibly severe bending at various points throughout the length, while in the third case expansion will be evenly distributed with negligible end movement.

In my view, installation in ducts or troughs is undesirable



(i)



(ii)

Fig. D

(i) Sheath temperature of 132 kV 0·25 in² single-core oil-filled cable buried in cement mortar and soil.
(ii) Cable configuration of 132 kV 0·25 in² single-core oil-filled cable.

and to be avoided wherever possible; preferably cables should be buried or on spaced supports. I have a preference for the latter. I suggest that where, owing to deterioration of paper caused by high-temperature operation, limitation of movement is an important consideration, the distinction between the behaviour in these three types of installation should be clearly borne in mind.

Mr. C. C. Barnes (*communicated*): Fig. 2 of the paper by Dr. Gazzana-Priaroggia *et al.* is important because it shows that the cable loading has only been moderate (calculated mean conductor temperature, 49° C), and in the absence of any soil thermal-resistivity test data a wide variation from the many assumptions made is possible. Similar data for cables A, B, C and D are not provided.

As these cables have only been lightly loaded, limited dielectric deterioration will be anticipated, particularly since cables A, B, C and D were operating at very low stresses, namely 54–67 kV/cm. Furthermore, cable C is exceptional in that it was manufactured in war time (1943) with inferior paper. The effect of low electric stress and unknown (but probably low) conductor temperature followed by a withstand test at a voltage corresponding to 2·5 times the working voltage only proves that the cables have withstood a very modest combined effect of temperature and electric stress.

The 1936 Paris 220 kV oil-filled cables were designed for a maximum stress of 94 kV/cm, but design stresses of this order were not adopted in Great Britain until more recently:

Voltage	Maximum stress	
	1940	1960
kV	kV/cm	kV/cm
66	75	100*
132	85	110

The 1949 fault referred to in Section 1 of the paper by Dr. Arman *et al.* was established as a failure by the manufacturer to appreciate the effect of variations in paper tensioning, and about the same time two other manufacturers had a number of drums of 66 and 33 kV oil-filled cables rejected owing to torn papers revealed as a result of bending tests. It is clear, therefore, that the apparent reluctance of users to adopt quickly higher electric stresses was due, until recent years, to the lack of high-precision paper lappers, controlled manufacturing techniques and testing equipment adequate for proving expensive pressure-assisted cable systems.

The authors do not detail the improvements resulting from the

* Oil-filled cables for a maximum stress of 100 kV/cm at 66 kV and 125 kV/cm for 132 kV service have recently successfully passed C.E.G.B. type-test requirements but so far, service experience is negligible.

use of carbon-black screening, but in Japan carbon-black screening of oil-filled cables has revealed

(i) Impulse breakdown stress about 5–15% higher.
(ii) A.C. breakdown stress about 25–30% higher, together with increases in the dielectric power factor and ionization factor.

What criterion is used by the authors for selecting an acceptable type of carbon paper, and how do they check that its characteristics will not alter during the life of at least 40 years expected for oil-filled cables?

Reference is made to lapping tension and humidity control. Are both these requirements essential, and to what extent does each contribute to improve breakdown strength? What are the optimum requirements for humidity control?

Tank impregnation has been standard practice in the cable industry for so many years now that it is surprising the authors had not appreciated the merits of this system earlier and adapted it to the requirements of the oil-filled system.

Specified type-test requirements are short-term tests to check, at modest expense, the manufacturers' long-term tests and research investigations mentioned in Section 3. Successful field experience is the final criterion. Laboratory testing is confirmed in service by a cautious but progressive implementation of development techniques.

The authors' reference to 'dielectric fatigue' (Section 3.1) is interesting. Can they give comparative test data for oil-filled and other types of cable insulation? Dielectric fatigue cannot be assessed by type tests as specified in Engineering Recommendation C.28.

The arbitrary 24-hour test at 2·5 times the working voltage has no intrinsic merit; oil-filled cables made in this country have proved satisfactory without this test.

The comparison of oil-filled cables and capacitor bushings is illogical as these two items of equipment are designed and manufactured on a different basis.

In Section 5.7 the recommended maximum time periods for 100°C conductor temperature and also specified time periods for higher temperatures will be helpful.

The observations on safety margin in Section 7 are interesting, but the authors must appreciate that, when using expensive pressure cable systems, users must be provided with detailed test information to justify the utilization of advanced designs. Furthermore, responsible users will invariably insist on some form of practical test to confirm the manufacturer's view.

Mr. S. C. Chu (*communicated*): In the paper by Dr. Arman *et al.*, I was disappointed in the lack of mention of pressure tanks, which are one of the indispensable accessories in an oil-filled cable installation. I understand that the design limits of the maximum and minimum pressures have been modified considerably from the early figures. Can the authors give comparative figures, and explain why such changes come about? Is it due to too conservative designs in the early stages or later improvement of mechanical design of the cable and its accessories? Would the authors comment on the possibility of designing oil-filled cables in the future to dispense with the pressure tanks altogether?

The authors mention that oil-filled cable systems can be subjected to conductor temperatures up to at least 110°C for a considerable period, but have omitted to mention the effect on the design of the oil system due to such a change.

In Section 2.3.3 the authors mention the use of a new equipment. Is there any change in the process of degassing the oil? In view of possible oxidation, do the authors consider that degasification should be carried out at a temperature lower than 100°C, say 80 or 60°C?

With reference to Section 2.2(*f*) of the paper by Dr. Gazzana-Priaroggia *et al.*, have the authors measured the power factors of individual paper layers from the conductor to the screen? These 'radial' power factors are usually higher at the conductor and also at the external screen than the intermediate layers. They can be used for comparing the uniformity of ageing in cables.

I note that the oil was tested at 100°C instead of 80°C. At 100°C the results may be affected by oxidation of oil. The stress of 0·5 kV/mm used for testing oil is low compared with that in a cable. Do the authors consider that a power-factor test on oil at a high stress is desirable?

Mr. R. W. Langley (*at Brighton*): The authors have shown that present cables can carry a higher load and consequently withstand a higher temperature than has been allowed in the past. Whilst this is very satisfactory, great care is necessary if damage is to be avoided owing to through short-circuit currents. The speed of operation of the protection, and that would include any back-up facility, must be such that a fault, which might be outside the zone of the oil-filled cable, is cleared sufficiently quickly to prevent damage to the cable. When operating at 110°C this does not leave much margin, and I should be interested to have the authors' comments on the effect of these proposed increases in temperature on the short-circuit rating.

A further point of considerable importance is the question of alterations to ratings due to changes in the thermal resistivity of the soil. This is mentioned in Section 5.6 of the paper by Dr. Arman *et al.*, but very little information is given which is likely to be of use to the installation design engineer.

The condition which could well arise is that an uprating of the cable to a maximum temperature of 110°C for the present soil thermal resistivity might cause a derating to be applied due to drying out of the soil surrounding the cable. If one were contemplating running at these temperatures it would be desirable to have some form of monitoring of the thermal resistivity of the soil, or alternatively, of the sheath temperature. The latter would probably be more practical and could be done from the tank or joint pits over existing pilots to give an alarm when the maximum permissible temperature had been reached.

The question of suitable back fills to obtain the best operational conditions with given subsoils is now under investigation as the authors have indicated, and it is hoped that more positive recommendations will soon be available.

The cable samples removed from service and the test results obtained on them were most interesting. It would have been useful if tests had been taken and plotted in Fig. 1 for temperatures up to 110°C and perhaps in addition some indication given of the order of power factor when the cables were new. Power-factor tests are generally considered to be a useful indication of changes in the state of insulation, but only on a comparison basis. Perhaps the authors could give some comment on their findings in this connection.

Comparisons between samples (*a*), (*b*) and (*c*) are most interesting since we have 23, 9 and 14 years, respectively, for the oil/paper combinations in service. The aluminium conductor cable in (*c*) shows a distinct difference from those of (*a*) and (*b*) where copper is used. Not only is the power factor lower but the relative positions of the curves for the different temperatures are reversed. Is this due to the paper quality, referred to in Section 2.2(*b*), or is it due to the different effect of aluminium to copper? A further reason might be the cable loadings during service.

No mention has been made of the effects of the pressures within the cable. Can it be assumed that these are quite unimportant from the point of view of impulse and 50 c/s breakdown and also deterioration of oil and paper?

There is no doubt that the record of insulation performance of oil-filled cables has been extremely good, and we as users have every confidence. This confidence does not, however, extend to the outer sheaths and protective servings which have been used in the past; it is there that the oil-filled cable shows its greatest weakness. Oil leaks, their detection and repair must cost the industry a considerable sum, and it is on this subject that there is room for considerable improvement.

On the question of oil leaks, the experience using lead with silicon-bronze reinforcement has not been entirely satisfactory, and there appear to be many advantages in the use of aluminium both for strength and reduction in weight. The susceptibility of aluminium to corrosion presents a problem, and an impervious layer of p.v.c. or similar material either in the form of tapes or extruded sheath is now common practice. This again has not been entirely satisfactory, and it would seem that some further work is necessary to obtain a finish which is non-corrodable to a degree comparable with lead—either by alloying or anodizing—and to rely on the outer covering for protection from mechanical damage.

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSIONS

Drs. A. N. Arman and **F. J. Miranda,** and **Mr. G. R. Bishop** (*in reply*): In reply to Mr. Goodall we would remark on the difficulty of assessing the effects of individual physical characteristics, such as impermeability and density, which are often concomitant and not readily dissociable. Our researches, fully confirmed by the data published by Salvage and Gibbons (Reference 4 of the paper), show impermeability to be the factor contributing towards higher electric strength. Greater density can cause an increase in power factor, but this is avoided by using high-impermeability normal-density papers now commercially available. The power factor of oil has a relatively small effect on the power factor of the cable, and measurement at about 10 kV/cm, coupled with a stringent specification, has, in our experience, been found satisfactory.

Although generally accepted as an international standard, several criticisms have been levelled against the 24 h test at 2·5 times the working voltage. In reply to Mr. Barnes, we consider that the intrinsic merit of this test is to ensure balanced development of both a.c. and impulse characteristics of complete cable systems. We agree with Mr. Banks that the test is an arbitrary one, but so are any other accelerated tests designed to prove long-term performance. Mr. Goodall's suggestion that the over-voltage factor should be graded according to cable stress is sound if the test is used as an impulse test check on the cable only. It is not valid for the associated accessories since their design stress is independent of cable stress.

Mr. Buckingham, as well as cable manufacturers, is naturally concerned with effective anti-corrosion protection of aluminium sheaths. We agree that even the most modern servings are vulnerable to mechanical damage, but past service experience with all types of cable both in this country and abroad supports the view that this will in future not be a serious hazard.

Difficulty in establishing thermally the most unfavourable situation along the cable route at present limits the practical utility of thermal images, although wider knowledge resulting from current E.R.A. investigations into the effects of soil characteristics on cable ratings, together with controlled environments of the type described by Mr. Holdup, will undoubtedly mitigate this position.

Measurement of the temperature of emergent oil in systems which employ forced oil circulation would, we consider, have practical significance only in soil of fairly uniform thermal resistivity. It would not indicate hot-spot temperatures.

On tank impregnation, we assure Mr. Barnes that the process has been under consideration for some years, but essential technological problems have only recently been solved. It will ultimately be extended to aluminium-sheathed cables.

The behaviour of oil-filled cable dielectric under repeated high impulse stresses has been illustrated by Mr. Ball. The absence of dielectric fatigue is of great interest. Other than the data quoted for 'solid' 33 kV cables, no information to which we can refer Mr. Barnes appears to have been published on other types of cable.

Information regarding the effect on lead sheaths of temperatures occurring during short-circuits is incomplete, and a thorough investigation has recently been proposed. In the meantime calculation of short-circuit ratings continues to be based on assumptions of no energy dissipation and constant currents over the short-circuit period. Actual temperatures reached are likely to be about 200° C rather than the 250° C proposed for rating purposes.

The probable effects of conductor short-circuit temperatures mentioned by Mr. Langley are considered in Section 5.3 of the paper, and we would, in addition, confirm that short time at 160° C has no adverse effect on oil-filled cable insulation.

In answer to Mr. Gosling we would remark that Zein El-Dine and Tropper observed no dependence of electric impulse strength on electrode metal and that we have noted none in a.c. strength. In any case, electrode metal effects are eliminated by carbon-paper screens, which are used in cable for all voltage ratings in excess of 33 kV.

Our conclusion that oil-filled cable systems may safely be operated for limited periods at temperatures up to 110° C is based on work which has been proceeding for several years, and we would have regarded the evidence presented in the two papers as being sufficient to meet Mr. Orchard's charge of obscurantism. Additional support for our view is, moreover, provided by Mr. Halperin's valuable contribution to the discussion.

We cannot understand why Mr. Cherry singles out the carbon-paper screen as the type most likely to cause trouble. On the contrary, we consider that the inherent mechanical strength of this material makes it a safer screen than other types, such as metallized paper. The reliability and precision of modern factory equipment is such as to ensure that the most highly stressed cables can, without supernatural assistance from our staff, be offered with a safety margin equal to that of lower stressed cables which have given such satisfactory service in the past. In reply to Mr. Barnes, lapping tension and humidity must be simultaneously controlled to obtain the desired quality of lapping. There is a fairly wide range of relative humidities which give satisfactory results provided always that the chosen value is maintained within specified limits.

Mr. Skipper's views on the optimum design stress for 400 kV cables do not differ appreciably from our own, and, in consequence, we cannot accept Mr. Cherry's dictum that economic gain is necessarily ruled out by increased operating stress at the higher voltages. Above 400 kV the need for a new low-loss dielectric is increasingly felt and the search becomes more intense. There is, however, a 500 kV oil-filled cable system in service abroad, it being possible, for short runs, to accept the high loss level incurred..

Mr. Johnson in effect advocates a maximum normal operating temperature below 85 °C, and there are undoubtedly circumstances where this would be advantageous. Equally, there are others under which the user may require the cable to operate

temporarily under heavy overloads, and the possible temperature limits under such conditions have to be established and regulated.

We presume that the bushing to which Mr. Cherry refers is that used in the 132 kV 3-core stop joint (Fig. 9). As the joint is fully screened the field is radial and no intermediate electrodes are necessary to obtain the required field distribution. Very close control of the epoxy-resin casting process, linked with performance tests to destruction on samples, ensure freedom from internal voids.

No major change in design of pressure tanks has been made since the early installations of oil-filled cables were effected, the only factor of importance being an increase in maximum operating pressure to 76 lb/in^2 dating back to 1938. This increase was possible owing to improved pressure element construction and the introduction of 'pre-pressured' elements. Oil-filled cable systems operating without pressure tanks are possible, but whether such a system is adopted is a matter of economics. In reply to Mr. Chu's further questions, no change has been made in degasification technique, and the temperature chosen depends on the physical characteristics of the oil and not on the possibility of oxidation.

Drs. P. Gazzana-Priaroggia, G. L. Palandri, and U. A. Pelagatti (*in reply*): Before replying in detail to the discussion of our paper we wish to report on some additional tests made since the paper was written, which confirm and extend our conclusions.

A series of tests similar to those described in Section 3.1.3.7. have been carried out on tubular capacitors obtained by interleaving and rolling metal foils and paper sheets.

The capacitors were introduced into glass test-tubes provided with metal leads sealed to the glass for connection to the capacitor electrodes. The test-tubes, after drying and impregnation, were then flame-sealed.

These capacitors allowed direct and continuous measurement of the power factor at different temperatures and voltages during ageing. The results have substantially confirmed those given in Section 3.1.3.7, but we have noticed that these tests exaggerated phenomena due to metal-surface effects.

In fact phenomena of this kind are not so evident when the ratio between the metal surface in contact with the insulation and the volume of the insulation itself is of the same order as that in cables.

With reference to Section 3.2.3, the tests on the cables described have now run for 300 days, and we would like to give the results obtained.

Fig. E is Fig. 10 of the paper extended to 300 days.

As can be seen, the initial power factor at 40 kV (i.e. at 1·4 times the working voltage) is about the same for both cables, namely, 0·4%.

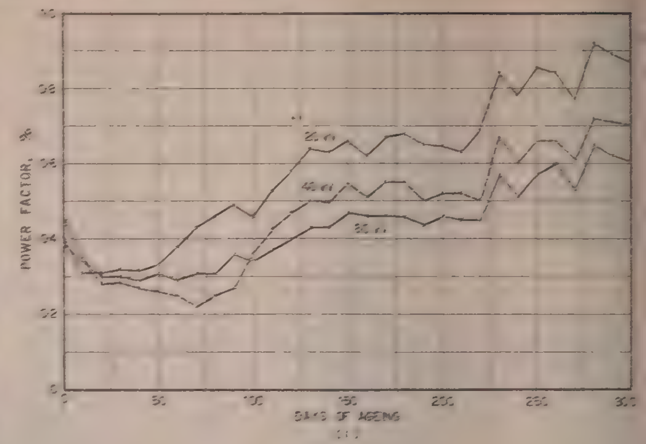
The power-factor difference between 20 and 80 kV for the screened cable is about six times that of the unscreened one, but after 100 days' ageing the situation is completely reversed.

The carbon-black screened cable shows practically zero power-factor difference, whereas the unscreened cable has a negative power-factor difference of about 0·15%. This situation remains unchanged up to 230 days, when the folding strength of the cable paper is reduced practically to zero.

Fig. F(i) is Fig. 11 of the paper extended to 300 days. Fig. F(ii) shows the same effect for a cable provided with carbon-black paper screening. The results in this Figure are in substantial agreement with those of Fig. E.

All the above power-factor measurements have been carried out at 120° C.

Fig. G shows the power-factor changes for the cables of Fig. E during 250 days' ageing at 120° C, but with the measurements



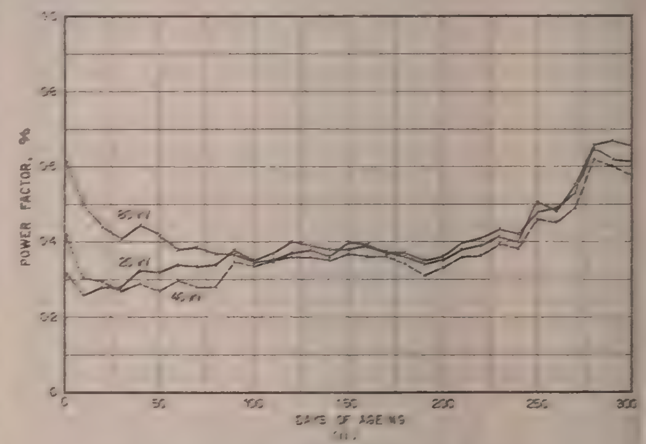


Fig. E.—Fig. 10 of the paper extended to 300 days.

(i) Unscreened conductor.
(ii) Carbon-black paper screening of conductor and insulation.

taken at 40 kV (corresponding to a maximum stress of 100 kV/cm) and 85° C, i.e. a temperature which is normally considered as the maximum permissible operating temperature for oil-filled cables.

As can be seen, the initial power factor of the unscreened cable is 0·2%, but it increases steadily up to about 0·45%, whereas the initial value of the carbon-black screened cable is 0·33%, but it decreases after 30 days to 0·22% and remains practically constant up to 250 days' ageing.

The change in power factor when measured at 85° C and 40 kV in the case of heat cycling up to 120° C and continuous application of voltage (40 kV) does differ substantially from the results for the case of continuous application of temperature, as can be seen from Fig. H, which refers to tests carried out on the same cables as in Fig. F.

These results clearly show the beneficial effect of carbon-black paper on power-factor stability up to 120° C and for periods of time appreciably in excess of the expected life of a cable based on paper deterioration.

Mr. Goodall asks at what percentage of paper deterioration one is to draw the line and regard the cable as unsafe. We are of the opinion that 90% (i.e. reduction to 10% of the original characteristics) would be a reasonable limit.

In reply to another point by Mr. Goodall, we have always noticed that buried cables, if suitably cleated at the ends, do not move appreciably.

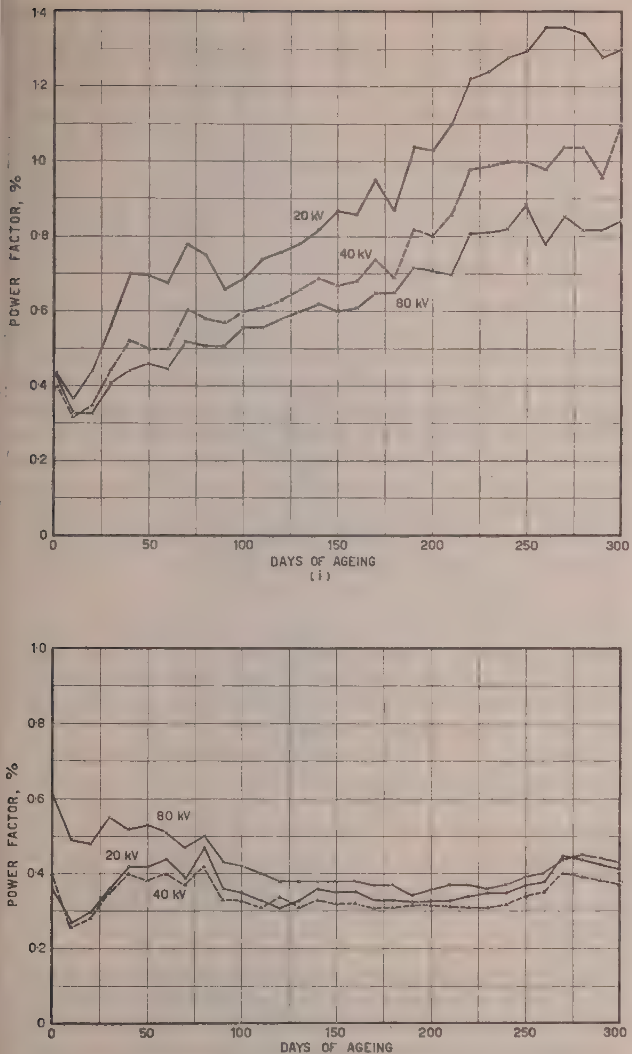


Fig. F.—Fig. 11 of the paper extended to 300 days.

(i) Unscreened conductor.
(ii) Carbon-black paper screening of conductor and insulation.

Dr. Williams would have expected paper deterioration to have less influence on cable characteristics than oil deterioration. We confirm that our tests have shown that the only important oil deterioration taking place is due to the contamination by the deterioration products of cellulose.

With regard to the percentage of moisture which can be tolerated in a dielectric working at 16kV/mm at 120° C, we believe it is about 0·1% by weight.

The statement in Section 2.1, with regard to the 'significant information' obtained from the oil taken from a Paris cable, simply means that the information obtained from that oil was not affected by erratic factors as in other cases, and that the characteristics were in fair agreement with those observed in laboratory investigations carried out under controlled conditions similar to those occurring in service.

We do not share Dr. Williams's fear that the power-factor/stress phenomenon resulting from the use of carbon paper could conceal some defects in cable construction. No gross defect in a dielectric screen would give rise to the same type

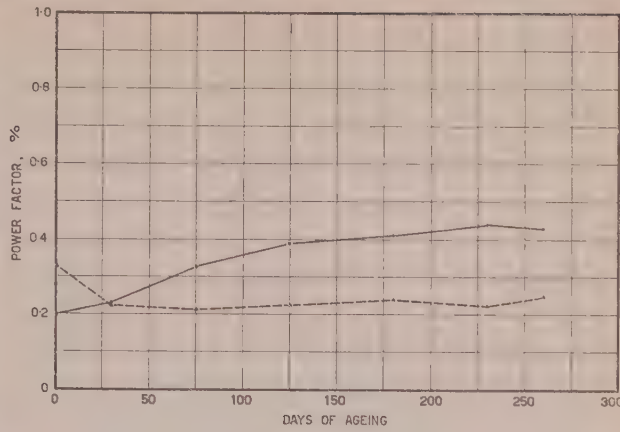


Fig. G.—Effect of continuous application of temperature (120° C) and voltage (40kV) on power factor at 85° C and 40kV of a 50kV oil-filled cable.

———— Unscreened conductor.
— — — — Carbon-black paper screening of conductor and insulation.

of power-factor/stress increase as is observed on carbon-paper-screened conductor cable.

Perhaps we did not make it sufficiently clear that the carbonization of the oil due to the absence of external screen on the cable insulation mentioned in Table 1 did not occur in service, but during the application of a test voltage of the order of 4 E_0 for rather a long time (6 to 7h). Anyway, it can be seen from diagrams (*a*) and (*b*) relating to such cables that, notwithstanding the absence of the outer screen, no appreciable power-factor increase was detectable up to about 2 E_0 (75kV).

It is not possible to give in a few words an explanation of the carbon paper phenomena, but we are planning to present a theory supported by experimental work in a forthcoming paper.

In reply to Dr. Gosling, we are of the opinion that the physical parameters given for the oil in our paper are sufficient to define it also from the point of view of gassing properties. Reference to this is made in a paper by two of the authors.*

The part played by particles in the oil in the a.c. breakdown is stressed in another paper by two of the authors.†

We have evidence that deterioration of the paper begins at temperatures also much lower than 100° C.

We have no test data on paper deterioration at pressures higher than atmospheric.

Mr. Halperin states that in our paper insufficient evidence is given that oil-filled cables might operate successfully at a maximum stress of 16kV/mm. This is perhaps true, but we consider that the required evidence is given in Table 2 of the paper by Dr. Arman *et al.*

Mr. Halperin also thinks that the folding test on paper seems too severe a criterion for deterioration. We believe that it is a very significant criterion for ageing, even though it does not necessarily represent a precise requirement for the service performance of a cable.

We do not understand the facts on which Mr. Cherry bases his statement that 'a slight crease . . . particularly with carbon-black stress tapes would be almost impossible to detect'. We do not know of any method to detect creases on test on oil-filled cables with or without carbon paper.

However, modern super-high-voltage cable factories are now

* Palandri, G., and Pelagatti, U.: 'Gli oli isolanti per cavi elettrici', Paper presented at the Associazione Elettrotecnica Italiana Annual Meeting, Bellagio, October, 1954

† Gazzana-Priaroggia, P., and Palandri, G.: 'The Influence on the Oil Dielectric Strength of the Gas Pressure in Equilibrium with the Oil', *Journal of the Electrochemical Society*, 1960, 107, No. 11.

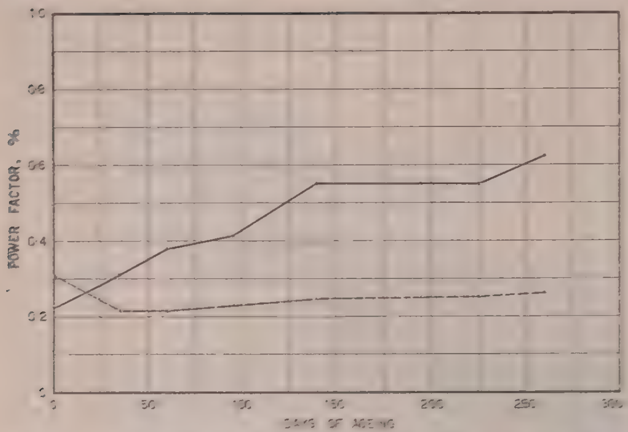


Fig. H.—Effect of heat cycling up to 120° C and continuous application of voltage (40 kV) on power factor at 85° C and 40 kV of a 50 kV oil-filled cable.

——— Unscreened conductor.
— — — Carbon-black paper screening of conductor and insulation.

equipped with such high-precision machinery that, with suitable quality control, complete absence of manufacturing defects can be guaranteed.

In reply to Mr. Johnson, Fig. 12 is an approximate guide like the 10° C rule. However, several points of the diagram have been checked and found to be consistent with practical experience. We do not think that from 120° C to 50° C there is a reaction change in the deterioration of the paper. In any case, all possible errors would be in the sense of obtaining more conservative results for all temperatures lower than 120° C.

The moisture content of the paper submitted to life tests was of the order of 0·1%. The moisture content according to the findings of some authors plays an important part in the reaction rate only when larger than 1% (see Reference 17 of the paper).

Mr. Barnes asks what criterion is used to select an acceptable type of carbon paper. In the early development of a type of carbon-black paper suitable for super-high-voltage oil-filled cables a rather elaborate specification was introduced which provides adequate guarantees that it will not alter for all the cable life.

With regard to the questions raised by Mr. Chu, we have found that 'radial' power-factor measurements did not provide significant information.

According to our experience and testing methods, the test carried out on the oil at 100° C does not produce any oxidation. Tests on the oil alone at very high stresses would be very interesting, but we doubt whether these are possible without introducing solid barriers in series with the oil, which would be quite undesirable.

Replying to Mr. Langley's questions regarding the difference between (c) and (a) and (b) of Fig. 1, we do not attribute this to the use of aluminium instead of copper but rather to the different cable loadings in service.

We have evidence that the pressure in the cable is of little importance to the impulse strength, but is of great importance to the 50 c/s strength (see Reference 16). We have no evidence of the importance of pressure on the deterioration of the cable, but we think that it should be small.

DISCUSSION ON 'A BASIS FOR SHORT-CIRCUIT RATINGS FOR PAPER-INSULATED CABLES UP TO 11kV'*

Mr. J. Wainwright (*communicated*): During the examination of some piece of equipment which has failed, it is often helpful to be able to estimate the temperatures to which the insulation has been subjected. For this reason Section 2 was of considerable interest.

Although careful examination would probably make it clearer, I found some difficulty in deciding on whether the paper was impregnated or not during the charring test. Section 2.1 states that the paper was examined without impregnant, but presumably this means that the impregnant was removed after the heat source had been applied rather than beforehand.

In addition to the degradation of the papers it would be interesting to consider the effect of the high temperatures on the impregnating medium. A temperature which was not high enough to produce charring of the paper could presumably cause some damage to the impregnant either by oxidation or even 'cracking'. Although this may not be very important in the low-voltage cables considered by the authors, I would be interested to have their views on the possibility of its happening, and if it did whether it would constitute a danger in very-high-voltage cables. Were any tests made in this very extensive investigation to determine if any change had taken place in the impregnant? It would seem that tests such as those based on infra-red absorption characteristics would have been useful in this instance.

Dr. Mole (p. 208) mentioned that the presence of moisture in the paper would accelerate the rate of ageing. Would not the presence of moisture also tend to keep the temperature of the paper down, owing to the high latent heat required for evaporation? Compared with the 75 cal/g assumed in Reference 7, the moisture would need some seven times as much heat to evaporate unit mass.

Messrs. L. Gosland and R. G. Parr (*in reply*): The tests described in Section 2.1 were made on papers freshly removed from a cable with minimum exposure to air and containing a full amount of impregnant. After the tests the impregnant was washed out to facilitate visual examination.

The possibility of deterioration of the impregnant at temperatures sufficient to char the papers was considered at an early stage, but the subject was not examined in detail, because it later became apparent that other features would limit conductor peak temperatures to about 160° C and sheath temperatures to a figure not much higher. At such temperatures and for the times in question, mineral oil may be regarded as quite stable (cf. the subjection of oil to 150° C for 45 h with copious supplies of oxygen in the sludge test of B.S. 148), and the customary additives are likely to be no less so. We think it unlikely that this effect will constitute a danger with very-high-voltage cables.

The moisture content of the paper in cables in good condition is less than 1%. This greatly limits the value of its useful effect which Mr. Wainwright has mentioned.

* GOSLAND, L., and PARR, R. G.: Paper No. 3314 S, August, 1960 (see 108 A p. 183).

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DISCUSSION ON

'MAGNETOHYDRODYNAMIC GENERATION OF ELECTRICITY'

The discussion, which took place before the SUPPLY SECTION, 15*th March*, 1961, *was opened by D. J. Harris, B.Sc.(Eng.), Ph.D., Associate Member, and P. L. Davies, B.Sc., Ph.D.*

Dr. D. J. Harris: Significant progress has been made in recent years towards increasing the efficiency of conventional large-scale power-generating plant, but the maximum efficiencies achieved are still of the order of 40% and further success is likely to be hard won. The search for alternative generation schemes is therefore an urgent one, and methods suggested include fuel cell, thermoelectric and thermionic diode generators, as well as the magnetohydrodynamic (m.h.d.) generator. In the m.h.d. generator a high-temperature gaseous working fluid is made electrically conducting and allowed to interact directly with a magnetic field to generate electricity, rather than to cause it to drive a turbine coupled to a rotating electric generator. In the new scheme there are no high-temperature highly stressed moving parts, and the temperature of the working fluid can be increased considerably, with the consequent possibility of a higher efficiency. Since the emergent gas in the m.h.d. generator still has considerable kinetic energy, the generator will need to be followed by a conventional generator or other generating device.

A high-temperature high-velocity gas stream can be produced by burning fuel such as pulverized coal or petroleum fractions, e.g. kerosene, directly in air and expanding the hot gas through an appropriate nozzle. The gas will then contain the products of combustion, which are generally undesirable components, since many of them have electron-attaching properties. Alternatively, a heat exchanger can be used to transfer the energy from the burning fuel to a gas in a closed cycle. The former method gives higher gas temperatures than the latter, although the free choice of gas allowable in the closed cycle is a great advantage. For induction-generation schemes, pulsed combustion chambers can be used, the pulsed nature allowing higher temperatures to be achieved during actual combustion. A gas temperature of 2000° C and a velocity of 1000 m/s are typical of what can be achieved by present techniques.

The high-temperature gas used as working fluid can be made electrically conducting in a variety of ways, but all involve the ionization of a fraction of the gas. Perhaps the most promising method is that in which a low-ionization-potential element, e.g. sodium or potassium, is injected into the gas, some of which becomes thermally ionized. The fraction of the total gas ionized is likely to be less than 1%, however, with an electrical conductivity of the order of 100 mhos/m. While this conductivity is low, use will have to be made of such a conductor if the scheme is to work. In order to extract energy from the gas a braking force must be exerted on it, and this is most conveniently done by imposing a suitable magnetic field. A magnetic field transverse to the direction of flow will induce an e.m.f. in the gas, a current will pass through the gas and a braking force will be imposed. Electrodes inserted in the gas will transfer the electrical energy to an external circuit. Alternative schemes in which either the flow of the conducting gas or the actual conductivity of the gas are periodically pulsed allow induction methods of energy transfer to be used and no conductors are then required in the gas. Many alternative induction methods are possible, the energy being coupled in each case into inductor coils external to the gas. Pulsing frequencies of several hundred cycles per second would seem to be needed.

Whatever magnetic-field configuration is used, it is the charged particles in the gas alone that are initially braked. Since nearly all the gas particles are electrically neutral, it is essential that an effective transfer mechanism should exist between the charged and the neutral particles. Calculations based on extrapolated collision-process data suggest that there may be a rather low limit to the rate at which energy can be extracted from a practical gas. More work, both theoretical and experimental, is required before the feasibility of the generation scheme can be assessed with confidence.

Dr. P. L. Davies: Numerous calculations have been carried out principally by American engineers on the practical design of continuous m.h.d. generators. These one-dimensional flow analyses usually assume, for instance, that the magnetic Reynolds number is small, the conductivity of the gas is constant and scalar, the gas is electrically neutral and obeys the perfect gas laws, the only dissipation is the Joule heating of the gas when current is drawn and the system is free from the formation of shock fronts. The variables involved are normally pressure and temperature of the gas, the inlet Mach number, M_0, the electrical conductivity, σ, the velocity, u, the length of the channel, l and the channel width. The systems are described in terms of electrical efficiency (ratio of voltage output to open-circuit voltage), equivalent turbine efficiency and actual efficiency (i.e. power generated in load per unit heat power input). Design is based on the relationship between efficiency, inlet Mach number and a dimensionless interaction parameter ($\sigma B^2 l/\rho_0 u_0$) for different operating conditions; for instance, optimum overall efficiency or conditions in which one of the parameters, say velocity, pressure or channel area, is kept constant.

For a given value of this interaction parameter and loading the physical length of the generator will be inversely proportional to the electrical conductivity of the gas. This depends on the gas temperature, degree of equilibrium and presence of easily ionizable atoms and is complicated by other factors, namely the Hall effect and the motion of the ions relative to the neutrals. If the number of gyrations of the electrons between collisions with neutral atoms is appreciable, the effective conductivity of the gas is reduced. This reduction can, however, be limited by suitable choice of operating conditions. Furthermore, as the gas passes through the magnetic field momentum is exchanged between the neutral atoms and ions. The relative velocity between them influences the electrical conductivity, but the effect in m.h.d. generators being considered at present is likely to be small. From analysis it also appears that, for the velocity of electrons and ions to keep pace with one another along the channel axis, there must exist an ambipolar or balancing field in a direction opposite to that of flow. It is still to be shown how near this kind of physical picture implied in macroscopic calculations is to practice.

So far, details of experiments have been published by each of three research laboratories in the United States, with power outputs up to about 60 W/cm³ of duct. These experiments

attempt to show the feasibility of using partially ionized gas as a working fluid. The voltage/current relationships behave reasonably in accordance with the theory, and high equivalent turbine efficiencies are quoted. The actual efficiencies are probably less than 1%, but these might be improved considerably by increasing the channel lengths, which in these experiments are small. Design data have been produced for large-scale power production, at which level it is considered that the relative losses will have least significance. The outstanding problems would appear to be mainly concerned with engineering and materials, which are indeed formidable for continuous operation at temperatures of the order of 3000° K. However, there may be scope for invention in other ways of using high-temperature ionized gases as a working substance for the direct generation of electricity.

Prof. M. W. Thring: In 1954, I proposed this type of electricity generation, and was told that it could not possibly work. I have since discovered that Karlowitz had been working on it in America in about 1937 and he has said that, but for the war, he would have made it work. Therefore, the question whether it will work has already been answered. Stewart Way reported last year that he generated 6 kW for 2 min with quite reasonable efficiency. We have not very much in the way of an experimental programme in this country.

By combining the magnetohydrodynamic generator with a waste-heat boiler one can raise the overall efficiency of the cycle to about 60%, but if the adiabatic nozzle expansion ratio is large, the temperature after expansion is much lower than the maximum combustion temperature. This causes great difficulty in getting adequate thermal ionization, even with potassium seeding.

The other alternative, for a steady-flow generator, is to preheat the combustion air to 2000° C before combustion, but the best continuous preheater cannot give more than 800° C at present.

I have proposed the use of a striated combustion system where a thermodynamic working fluid occupies nine-tenths of the volume while a layer of highly conducting gas stretches right across the magnetic field and connects the electrodes.

Reynst showed that pulsating combustion could be at constant volume instead of constant pressure giving a high velocity without compression.

Lastly, we can put two 2-stroke cylinders opposite each other and blow an aluminium piston backwards and forwards through a magnetic field with graphite electrodes to generate alternating current. Then we can eliminate the piston, make the system much larger and blow a detonation wave backwards and forwards down the tube (valves at the ends).

These are just ideas to illustrate the point that the classical m.h.d. cycle is always subject to this great difficulty of the gas conductivity.

If we had a national programme of research into this problem we should eventually develop a system which could have a generation efficiency of 50–60%.

Dr. I. Estermann (*United States*): In America we have been concerned with m.h.d. mainly in connection with direct conversion of nuclear energy into electric power. We feel that this conversion is at present realized in a rather clumsy way and that we do not utilize the really attractive part of nuclear power in a proper fashion. We have too much waste of temperature potential in our various conversion processes, which ultimately results in a relatively high cost.

Our main concern at present is with materials problems, which are of the same kind as those preventing the achievement of very high thermal efficiency in conventional power plants. The materials problems involved in m.h.d. conversion are not quite as rigid as those involved in attempts to improve the thermal efficiency of turbines or other mechanical systems, because the stress requirements are probably somewhat less. But even with the lesser stress requirements, the increase in temperature that is necessary to make the process more attractive leads to an almost exponential increase in the difficulties that the materials will present.

These difficulties are both mechanical and chemical. We have dealt with mechanical problems, namely softening and loss of strength, and with chemical problems, namely oxidation and corrosion. We will have to do much more materials research before we can go into the detailed engineering design of a particular device. Thus, any national programme such as that suggested by Prof. Thring should include a considerable effort on research into high-temperature materials.

We are also considering other unusual forms of energy conversion, such as have been mentioned by Dr. Harris, namely thermo-electric conversion, thermionic conversion and fuel cells. I think that thermionic and thermo-electric conversion should be considered in the same framework as m.h.d., because they involve the same type of parameter, and, to a large extent, materials problems rather than problems of basic science or even basic engineering.

Fuel cells are probably closer to realization than any of the other devices, but they will have necessary limitations because of the cost of the fuels which have presently been found suitable. Here, the main problem is to find a fuel cell which will operate with cheap, conventional fuels of the type used in other thermal power plants, such as hydrocarbons. This is where our main effort should be applied at present.

Mr. J. S. T. Looms: Experimental data on gases which are partly ionized thermally are not plentiful. As a first step in obtaining such data, we have made some measurements on argon heated electrically in a plasma jet. Temperatures up to 13000° K are obtainable in gases at atmospheric pressure in such jets.

We used a pair of water-cooled probes immersed in the jet, at different points and with different spacings. We applied potential differences up to 12 V and measured the currents. Approximate values only of apparent conductivity have been obtained for three main reasons:

(i) Because the current flow was found to fluctuate violently with time so that only average values were obtained. Periodic variations attributable to ripple in the heating supply were also observed.

(ii) Because the probe circuit did not obey Ohm's law but behaved in a way which suggested that ion sheaths were present.

(iii) Because current from the heating circuit leaked into the measuring circuit.

We found a roughly linear relation between input heating power and apparent conductivity, the values ranging from about 0·05 mho/cm at 5 kW to 0·8 mho/cm at 18 kW, with large variations depending on the probe potential difference. We estimate that the temperature range was between 4000 and 10000° K; the apparent conductivities were calculated on the gross assumptions that the gas conducted solely and uniformly between the probes. The experimental data are consistent with ionic conductivity in an electrode sheath.

Our oscillograms, high-speed films and microwave and photomultiplier observations showed that the jet was in rapid turbulent motion, varied in luminous intensity and probably contained 'bubbles' in which the degree of ionization was abnormally high.

Mr. R. G. Voysey: Most of us wish to assess the future of this device which is macroscopically simple but very complex at the microscopic level.

Thermodynamically attractive, its present practical efficiency is very low. The rapid 19th-century progress in generation by the

Faraday effect followed from the unique conduction properties of metals, and the difficulties of this device stem from the abandonment of metal conductors.

Two applications may be imagined. High power/weight ratio may make it attractive for transportable electricity supply, already committed to clean, ash-free fuels, but other special advantages may be required to compensate for its efficiency being only about one-twentieth that of existing prime-movers.

The second application is in industrial electricity supply, where, operating as a 'topping' unit, its exhaust losses could be recovered in the conventional steam boiler. Some minimum efficiency is still required to repay the capital cost of the device which may be related to its fluid throughput. An elementary sum suggests that the lower limit of attractiveness may be about 4%—somewhat more than has been achieved so far.

The important losses in this device are not in the cycle thermodynamics but in the energy transfer mechanisms, and I hope there will be better analysis of the latter. Experimental studies of resistive gas conduction are not perhaps relevant to the generating case. Oscillations which occur so readily in degenerative conduction in arcs should arise even more easily under generating conditions. Perhaps they will allow further m.h.d. applications, although their frequency should be much above normal power frequencies.

M.H.D. generation has to be developed in competition or in conjunction with nuclear energy, for in little more than four years we should have a much sharper appreciation of the economic status of the latter.

Mr. P. D. Dunn: The basic problem in m.h.d. generators is that of obtaining adequate electrical conductivity. One can use the ions in thermal equilibrium with the hot gas or raise this level of ionization to a non-equilibrium value by r.f. or d.c. discharges or as proposed by Prof. Thring by injecting fuel into the interaction duct.

Considering first the non-equilibrium methods, it is seen that ions are very costly in energy, taking about 10 eV compared with a thermal energy in the beam of, say, 0·2 eV. Hence for even a low degree of ionization of the order of 1%, it is possible to have 50% of the total energy locked up in the beam in the form of ionization energy. This might not be too serious if the level persisted, but it is found that, at pressures of about 1 atm, recombination rates are of the order of microseconds compared with milliseconds of interaction time. One is therefore led to the conclusion that, if one has any spare energy, there is little advantage in doing other than insert it in the combustion chamber with the rest of the fuel.

Returning to thermally produced ions, we can readily calculate the number using Saha's relation, and hence conductivity from the relation

$$\sigma = \mu n e$$

where σ is the electrical conductivity, μ is the mobility, n is the number density, and e is the specific charge.

There are two alternatives open: we can use a readily ionized vapour such as caesium, or alternatively an inert gas, say helium seeded by a small percentage of caesium. In the latter case the number density will be lower, but this may be compensated by a higher electron mobility. Mobility can be calculated if the appropriate electron neutral collision cross-sections are known, as, for example, under the conditions of high electrical field/pressure met in controlled thermonuclear work. Unfortunately little is known for the low-energy range and the high pressure in m.h.d. generators. It is the uncertainty in the correct values of mobility and cross-sections which renders it difficult to assess which system it is to be preferred. The real need is for reliable conductivity measurements under our conditions.

With regard to what Mr. Voysey said, m.h.d. systems could be applied to nuclear reactors, although they are perhaps an order of magnitude more difficult than, for example, thermionic generators, since they do involve extracting a very hot jet of gas from the reactor in addition to the difficulties of the conversion itself. Hence one can say that thermionic diodes are the first generation when applied to nuclear reactors, and one should consider m.h.d. generators for closed-cycle systems as higher-temperature reactors are developed.

Mr. D. T. Swift-Hook: Drs. Harris and Davies mention the problems of conductivity from the *microscopic* point of view, but in the United States 200 kW have been generated, representing 6% of the kinetic energy of an oil flame, and so these problems need not worry us too much. There are other basic problems of a *macroscopic* kind, as well as engineering problems, which should be considered. In the C.E.G.B. we have generated small amounts of power (1 W or so) also from an oil burning rig.

Three basic problems may be solved if pulsed systems such as those mentioned by Dr. Harris and Prof. Thring can be used. First, the mean temperature which the materials have to stand will be low, while the interaction temperature remains high. Secondly the electrodes may be dispensed with if inductive coupling can be used, and thirdly alternating current can be generated instead of direct current. The C.E.G.B. is running small pulse jets (the type of engine used in the German V1 flying bomb) and resonating flames to pulse the actual gas flow, and various methods of inductive coupling are being tried.

The problems of wall friction and heat losses, and also of providing a magnetic field over a long length may be overcome by using the vortex generator invented by Petersen (in 1918). Imagine the m.h.d. duct wrapped round in a spiral; the inside walls can then be removed to give a long spiral path for the gas flow in a compact space. Work is in progress in the United States on such a device.

I agree with Mr. Dunn that extra-thermal ionization does not appear economic, but it is certainly valuable experimentally, and we are setting up a closed-cycle device using low-temperature mercury vapour to study m.h.d. interaction.

On the engineering side my own view is that conventional fuels look more promising than nuclear ones since there is no high-temperature heat-exchange problem. One solution to materials problems may be to water-cool the walls to some extent and to use the tremendous heat losses to the water to raise steam; it has already been emphasized that the m.h.d. generator is seen as a topping device to be used in conjunction with steam plant. Coal in the form of pulverized fuel obviously presents difficulties with burners, fly ash, etc., but it may be economic to use cheap gas from gasified coal. To achieve the necessary flame temperatures (around 3 000° C) oxygen-enriched air with pre-heat may be used.

Mr. A. M. Cassie: The energy transfer from the moving gas to the ionized particles in m.h.d. conversion seems to provide a constant topic of contention. Dr. Davies has followed the procedure currently adopted in high-temperature plasma analysis of deriving expressions in terms of cyclotron frequencies, but a clearer and more fruitful picture can be obtained by using mobility as the operative quantity.

In a weakly ionized gas, the mobility μ is defined by $u = \mu E$, where u is the relative velocity produced by the electric field E. The force on the particle of charge e is eE, and so the mechanical force on a particle moving with velocity u relative to the gas is $F = \frac{e}{\mu}u$.

In equilibrium this force must be equated to the motor

force on the cross-current in the gas, which leads to a particle velocity

$$v = \frac{u}{1 + k\mu^2 B^2 \times 10^{-16}}$$

and a cross-current density

$$\frac{kne\mu BU \times 10^{-8}}{1 + k\mu^2 B^2 \times 10^{-16}}$$

where U = Gas velocity, cm/s.
B = Magnetic field, gauss.
μ = Mobility, cm/s per V/cm.
e = Particle charge, C.
$(1 - k)/k$ = Ratio of external to internal resistance.

When there are two kinds of particles, ions and electrons, of very different mobilities, μ_i and μ_j, an axial field is set up given by

$$E = \frac{k\mu_e UB^2 \times 10^{-16}}{1 + k\mu_i\mu_e B^2 \times 10^{-16}}$$

which is characteristically about 10–100 V/cm.

The ions and electrons then move with the same velocity and a power output per unit volume

$$P = \frac{k(1 - k)ne\mu_e U^2 B^2 \times 10^{-16}}{(1 + k\mu_e\mu_i B^2 \times 10^{-16})^2}$$

which has a maximum value when

$$B = \frac{10^8}{(k\mu_e\mu_i)^{1/2}}, \text{ i.e. } V = \tfrac{1}{2}U$$

It is evident that, in the conditions of the m.h.d. experiments at present under discussion, the values of μ_e, μ_i, B, etc., are such that one is nowhere near passing this maximum. Indeed, so long as the factor $10^{-16}k\mu_e\mu_i B^2$ is small compared with unity, we must make μ_e as high as possible, even if μ_i is increased in the same proportion. This means that we must raise the temperature as high as possible and keep the density as low as possible in order to increase the fraction of the kinetic energy abstracted from the neutral gas per unit volume.

Mr. J. F. Barnes: I will deal with the statement by Dr. Harris that it will probably be necessary to operate an induction generator at high frequencies. Electricity might be generated at relatively low frequencies if sufficient inductive coupling can be obtained between the primary (i.e. gaseous) circuit and the load circuit of the generator by employing materials with high permeability in the core of the annular gap. For example, an output of 20 kW is obtainable (in theory) from such a generator 1 m long, with a transverse magnetic field of 1 Wb/m^2, coupled to the tail pipe of a V1 pulse jet engine operating at 50 c/s, expelling hot gases seeded with 1% potassium.

A more attractive form of such an induction generator is the one having a variable transverse magnetic field across the annular gap. By suitable matching of the primary and load circuits, equivalent turbine efficiencies, as defined by Dr. Davies, of 80% can be expected. If such a generator were to be used in a thermodynamic cycle similar to that proposed by Kantrowitz, it would be necessary to employ a maximum temperature of 2 900° K in order to obtain an overall thermal efficiency of approximately 55%.

The technological problems of trying to operate a practical generator at such high temperatures using a gas seeded with an alkali metal have already been mentioned. Furthermore the predicted thermal efficiency of 55% has to be compared with the value of about 50% obtainable far more easily from a complex gas-turbine cycle, with a maximum temperature of 1 500° K, rejecting its waste heat to a steam-turbine cycle operating at more conventional temperatures. The conclusion to be drawn from this comparison supports Prof. Thring's remarks that some alternative m.h.d. generator (e.g. using pulsed combustion or a shock-tube type of apparatus) would be more likely to become a practical device for generating electric power.

Dr. D. J. Harris (*in reply*): Many of the problems that will face a potential builder of m.h.d. generators have been discussed, and a great deal of work needs to be done before a successful and efficient generator is made. It is certainly possible partially to ionize the working gas jet, although energy requirements limit the degree of ionization to a fraction of 1%, and the best way of doing this is not yet settled. The very high temperature requirements of thermal ionization, with attendant materials problems, may be alleviated by the use of a surface ionization process, such as the ionization of caesium by a hot tungsten surface, which is effective at temperatures below 1 500° K.

Of the many alternative methods for extracting energy from the charged particles in the jet, induction methods seem the most attractive if sufficient coupling can be achieved. Considerable research is needed on electrode materials and processes, for the energy extraction method in which a transverse magnetic field is imposed on the gas.

The question of the degree of interaction between neutral gas particles—which carry most of the kinetic energy of the jet (>99%)—and the relatively small number of charged particles—which can be braked by the imposed magnetic field—is a very open one. Calculations based on available but rather uncertain collision data are rather pessimistic. Since this question is a really vital one, we have started a research programme in the Department of Electrical Engineering, University of Sheffield, to study the problem. An electrically driven shock tube of relatively low velocity is being used to simulate a pulse of partially ionized gas in a practical generator. An experiment using a homopolar rotating plasma generator as a laboratory source of quasi-steady moving partially ionized gas is also to be set up. In both cases the interaction between charged and uncharged particles during braking is to be investigated.

Whilst laboratory experiments are necessary to elucidate the individual processes that will occur, there is also a great need for large-scale experiments to investigate the behaviour of complete generator systems.

In spite of the many difficulties and unknowns which still confront us, the m.h.d. generation scheme has so many attractive features that there is every inducement and urgency for further work to be done.

Dr. P. L. Davies (*in reply*): I should like to confine myself to one or two further remarks on the interaction of partially ionized gases with magnetic fields and the transfer of energy to external loads. Mr. Cassie's treatment gives results which are entirely equivalent to those obtained by the usual approach, which I outlined at the beginning of the discussion. He prefers to express quantities in terms of mobility or electrical conductivity of the gas in the absence of a magnetic field, and his loading parameter is therefore independent of a magnetic field. Usually motion of the gas is treated as a whole and the slip between charged and uncharged components and Hall currents are interpreted in terms of an anisotropic electrical conductivity, which, together with the loading parameter in this case, are dependent on magnetic field strength.

When discussing the dependence of power output from a gas of given velocity on magnetic field strength, the results will be governed by which of the two defined loading parameters is deliberately kept constant. If the usual loading parameter is

selected, the power output increases initially with B^2, and at a sufficiently high value of B it approaches an asymptote. On the other hand, if the actual external resistance on the generator is maintained constant so that Mr. Cassie's loading parameter is independent of B, then, as he points out, the power output has a maximum value.

There seems to be an adequate theoretical explanation of the principle of m.h.d. generators, provided that assumptions underlying these treatments are satisfied in practice. However, this has not yet been fully confirmed in many of the devices being considered for power generation. The engineering problems are undoubtedly formidable, and it may be that other schemes such as high-temperature hydrocarbon-burning fuel cells, as mentioned by Dr. Estermann, may prove to be more practical in the long run for improving the efficiency of generating electricity from fossil fuels.

DISCUSSION ON 'OPEN-CIRCUIT NOISE IN SYNCHRONOUS MACHINES'*

Mr. P. L. Alger (*United States: communicated*): I have been interested in the subject of magnetic noise for many years and the more I have delved into it, the more fascinating it has become. It has been my observation that nearly all cases of objectionable magnetic noise (except for the large 2- and 4-pole machines) are associated with some form of mechanical resonance. For this reason it is desirable to check the natural frequency of the core by test. The authors give calculated values of the resonant frequency, without reporting any test results. Since the calculated natural frequency for Machine A is only half the impressed noise frequency, it appears that the machine would have made a great deal more noise if operated at 25 instead of 50 c/s, and also that there is a strong probability of production machines being near resonance if this factor is not checked in advance.

I have found that the frame structure may modify the resonant frequency considerably, especially for short and radially shallow cores. Also, it may create a dissymmetry, so that the vertical and horizontal modes of vibration have different frequencies. This has the effect of broadening the resonant frequency into a band that may be 50 or more cycles wide. Another factor shown by tests is that the weight of the windings adds to the effective inertia of the core, for vibrations in few nodes at least, but the percentage of the winding weight that is effective depends on the stiffness of the end windings, which in turn is affected by the winding temperature.

Thus, there are a great many obscure factors to be taken into account in trying to make an accurate prediction of noise. To investigate these it is most helpful to build a machine with an exaggerated noise tendency, as a synchronous machine with 162 slots and 28 or 32 poles, or an induction machine with rotor and stator slot numbers differing by only 2 or 4. Some results of studies along these lines are given in two papers.[A, B]

Mr. H. Headland (*communicated*): This discussion is directed towards application of the analysis by hydro-electric station designers who usually disregard the overall noise problem, because of the unknown effects of background, underground or overground construction and hydraulic machinery. Measurements are rare, but suggest about 90–100 dB. The Sudagai underground station[C] containing two 23 MW 250 r.p.m. vertical Francis units was soundproofed and the details are:

Station Dimensions	
Length × height × width	35·4 × 31·3 × 16·6 m
Structure Components	*Lining*
Inside wall: rock wall	Acoustic slate: rock wool
Arched roof	Acoustic aluminium tile and rock wool

Measurement Locations	*Noise Level, dB*
Generator room	80–81
Turbine room	91–93
Pumps and ventilation plant	94–101
Diesel room	105

These figures emphasize background noise and confirm our experience with auxiliaries and that hydraulic machine noise and cavitation dominates that from mechanical or electrical sources. The authors comments and calculated figures for the generators would be appreciated.

It would also be interesting to determine the noise spectrum for the 75 MW vertical motor-alternators for the overground station at Ffestiniog[D] and to know whether works measurements were made. Site tests may be made, but it might be mentioned that structure-borne noise was considered and that:

(i) The pump and turbine spiral casings are surrounded with microcellular expanded rubber and embedded in concrete.

(ii) The steel-framed building has an inner brickwork skin, cavity and masonry outer facing. Near the pumps and turbines, a plaster finish was chosen to deal with condensation and noise.

Data on hydraulic machinery noise is lacking,[D] and the only reference to the spectrum for centrifugal pumps seems to be that in Bruel's 'Sound Insulation and Room Acoustics'. An analysis therefore seems essential for study of overall noise, particularly for large reversible pump-turbines.[D]

High-output two-speed machines await development, and one problem concerns noise and vibration.[D, E] Dr. Walker's paper[E] gives details of a 200 MW 150 r.p.m. machine, and I should like to know the authors views on whether the noise levels from electrical or mechanical causes change with rotation, since this might justify separately driven fans. It would also be useful if their analysis could cover the noise characteristics as a motor at 167 r.p.m. or as a generator at 136 r.p.m.

The analysis shows *inter alia* that dimensions become important for large machines without mentioning noise levels for several machines operating simultaneously. Are the authors satisfied that overall noise level formulae apply under such circumstances?

Presumably the tests were made on horizontal machines with open-circuit ventilation and included bearing, brush and windage components. Could the analysis be utilized for vertical, enclosed, ventilated alternators and the design of their steel or concrete casings? The former may need heavy and costly structural design to avoid vibration, but an approach via electrical and aerodynamic effects might be worth while.

The authors views on resilient stator and rotor bracket mounting, ventilating-circuit sound-proofing and the application of the frequency analysis to their design would be welcome.

* Walker, J. H., and Kerruish, N.: Paper No. 3340 S, December 1960 (see 107 A, p. 505).

The North of Scotland Hydro-Electric Board's pumped storage station at Cruachan may have four 100 MW 1 100 ft-head reversible pump-turbines[D] with a speed around 600 r.p.m. While the authors confine themselves to 'open-circuit' noise and state that load effects are negligible, observations do not invariably confirm this impression. The authors' figures for the case where alternator output for forward rotation is less than the motor input with reverse rotation would be valuable.

Dr. J. H. Walker and Mr. N. Kerruish (*in reply*): Our experience of noisy machines, admittedly much less extensive than Mr. Alger's, does not fully confirm his statements, in particular that concerning the association of core resonance with noise level. We have data on only one machine, built about 20 years ago, on which there was clear experimental evidence of this phenomenon. This was a 600 hp 20-pole synchronous motor, operating from a 50 c/s supply. The outside diameter of the stator was 63 in; the gap diameter, 56 in; the core length, 11 in; and the number of stator slots, 126. According to our analysis the most likely noise harmonic here is a 600 c/s note, and this was confirmed by test. Our calculations predict (Fig. A) that there will be core resonance with this note at a

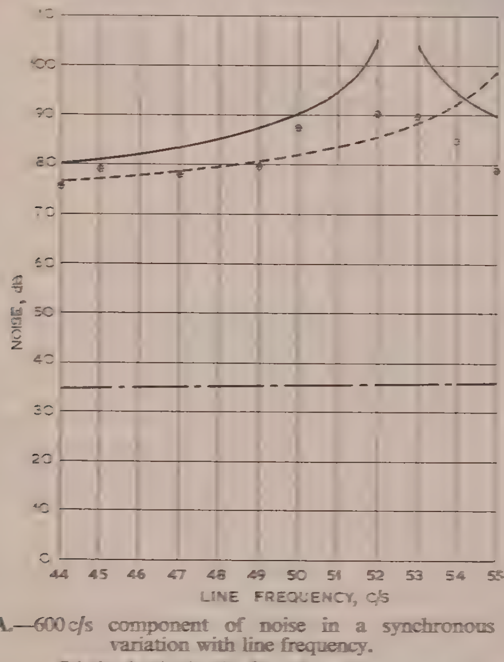

Fig. A.—600 c/s component of noise in a synchronous motor: variation with line frequency.

——————— Calculated, using inertia of actual core.
— — — — — Calculated, using inertia of core assuming outside diameter increased by ¼ in.
—— · —— · Calculated, using combined inertia of actual core and frame.
⊖ Test readings.

line frequency of about 52·5 c/s and that the noise level at 50 c/s will be 90 dB. As can be seen, both these values agree closely with the test readings. The dotted curve shows that, if the inertia of the core had been increased by increasing the outside diameter by ¼ in, the resonant frequency would have been increased by about 7% and the noise at 50 c/s decreased by about 10%. The chain-dotted curve gives the noise obtained by using the combined inertia of the core and frame, and thus confirms, as in our other examples, the assumption that the frame plays no significant part in magnetic noise of this type. Moreover, we have no evidence showing that the stator windings affect core vibration and our calculations, as stated in the paper, ignore this factor. The methods used by different manufacturers for attaching the core to the frame and for supporting the winding may, of course, play a decisive part in the generation of noise, and explain the divergencies between our experience and Mr. Alger's. As he suggests, a carefully designed experiment with a 32-pole machine having 162 stator slots would do much to elucidate these problems.

The noise data given by Mr. Headland for the Sudagai station will be of great value to all those concerned with the design of the electrical and hydraulic units and auxiliaries in hydro stations. We regret that, in the absence of design data of the generators in this station, we are unable to give a calculated figure for the noise. In the factory tests of No. 1 Ffestiniog generator/motor the predominant noise in the open shop was due to windage, and it was quite impossible to detect by ear any change in the noise level on opening or closing the field switch. This result is confirmed by our calculations, which, for the predominant note, give a figure of 13 dB. Only on site, with the noise due to the cooling air contained to a great extent in the pit, are readings of magnetic noise likely to be of value.

In general, magnetic noise usually occurs in short-pole-pitch machines such as industrial synchronous motors and Diesel-driven a.c. generators; normal hydro-electric generators with considerably longer pole pitches rarely exhibit such noise.

Since, however, on a digital computer the noise associated with a predominant harmonic can be obtained in under 10 minutes, and a noise spectrum in under 20 minutes, we are now carrying out this calculation as a normal procedure on all new designs. We would add that there would be no fundamental difficulty in using this programme to calculate the magnetic noise level of a 200 MW 167/136 r.p.m. change-pole generator/motor in either direction of rotation.

We have no data concerning overall noise level formulae, but it would be possible to check this point in the Ffestiniog station. Tests given in our paper were on horizontal machines with open-circuit ventilation, and, as far as possible, bearing, brush and windage components were eliminated by the normal technique. As already stated, the analysis can be utilized for any type of alternator irrespective of the ventilating system.

Our paper is confined to open-circuit noise, and we state that the change in the level on load is not appreciable. Magnetic noise, due to load, can, of course, occur; it is normally of twice line frequency only and is dealt with in detail in our paper on windings.[F]

Although some of Mr. Headland's discussion is outside the scope of the paper, his data, together with Mr. Alger's, will provide valuable supplementary information on the acoustical design of generating stations containing synchronous machines.

REFERENCES

(A) ALGER, P. L.: 'The Magnetic Noise of Polyphase Induction Motors', *Transactions of the American I.E.E.*, 1954, **73**, Part IIIA, p. 118.

(B) ALGER, P. L., and ERDELYI, E.: 'Calculation of the Magnetic Noise of Polyphase Induction Motors', *Journal of the Acoustical Society of America*, 1956, **28**, p. 1063.

(C) MIZUKOSHI, T.: 'The Sudagai Underground Power Plant, Japan', *Proceedings of the American Society of Civil Engineers: Journal of Power Division*, 1958, **84**, p. 1555.

(D) HEADLAND, H.: 'Ffestiniog and Other Medium-Head Pumped-Storage Schemes in Great Britain', *Proceedings of The Institution of Mechanical Engineers*, 1961, **175**, p. 319.

(E) WALKER, J. H.: 'Generator/Motor Problems in Pumped-Storage Installations', *Proceedings I.E.E.*, Paper No. 2853 S, February, 1959 (**107 A**, p. 157).

(F) WALKER, J. H., and KERRUISH, N.: 'Design of Fractional-Slot Windings', *ibid.*, Paper No. 2678 S, August, 1958, (**105 A**, p. 428).

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ELECTRICITY SUPPLY IN INDIA AND ITS FUTURE

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(*Lecture delivered before the* SUPPLY SECTION, 10*th May*, 1961.)

I am deeply conscious of the honour you have done me, an engineer from nearly half way around the world, in inviting me to speak to this august company of distinguished electrical engineers. I accepted your invitation with alacrity because I felt that I could not miss this opportunity of discussing the problems and the progress of the development of electricity supply in India. I firmly believe that the subject is one of importance and that it will have far-reaching consequences, not only to the people of the newly-independent Indian nation, but also to the United Kingdom, which is equally interested in a rise in the standard of living of the millions of our people.

My coming to this country once again is a happy pilgrimage. The pleasant memories of former associations here make me glad to be here at any time, and I am conscious of the traditions and ideals which are the common heritage of the British and Indian peoples.

India, one of the youngest and largest democratic republics in the world, is a secular State with a population of over 430 millions. Covering an area of 1 270 000 square miles, divided into 15 States with 14 official languages, it represents a colourful mosaic of races, religions and cultures.

India is richly endowed with natural gifts. In the north, we have the snow-capped Himalayas, crowned with Mount Everest. In the south lies the peninsula of Deccan, with the Arabian Sea washing its western shores and the Bay of Bengal the eastern. Between these two regions lies the great fertile Indo-Gangetic plain—the cradle of Aryan civilization, home of Indian art and culture. In contrast to this area, there is the great desert of Rajasthan and the dense forests of eastern and central India.

In India of today, we are fighting against odds. The outcome of that struggle will determine whether an under-developed country, with a vast population increasingly aware of higher standards of living elsewhere, can build a progressive economy, raise living standards, develop sound social institutions and achieve political stability within a democratic framework.

Electrical Energy in India

In spite of vast concentration around cities like Calcutta, Bombay and Delhi, the Indian economy is pre-eminently agricultural with 70% of its population engaged in the production of food-grains and cash crops.

Table 1 gives the distribution of towns and villages and the number of localities electrified up to 1960.

Table 1

ELECTRIFICATION IN INDIA, 1960

Population range	Number of towns and villages	Population $\times 10^6$	Number of towns and villages electrified	Electrification %
Over 100 000	73	24	73	100
50 000–100 000	113	8	113	100
10 000–50 000	1 257	24	1 041	83
Up to 10 000	560 000	307	20 200	3·6

The agricultural population is widely scattered in communities of less than 250–10 000 people in over half a million villages. Few villages with population below 5 000 have so far been provided with electricity. In fact, emphasis has been placed by the Government on industrial development during the second and successive Five-Year Plan periods.

The history of electricity supply in India dates back to the late 'nineties of last century. The first thermal power station in India, constructed in 1899 in Calcutta, has steadily grown into a major system catering for the needs of Calcutta and its suburbs covering an area of 500 square miles, with an installed capacity of nearly 500 MW and consumers numbering about 300 000. The first hydro-electric station (of 4 500 kW) was established in 1902 in Mysore State, for the mining industry in the Kolar gold fields. Electricity supply was confined to remunerative metropolitan, urban and industrial areas till the middle 'forties of the present century. The supply was characterized by extremely small demands for power and an almost imperceptible rate of growth. The aggregate plant installed capacity by 1939 was only 1 700 MW with an aggregate annual output of 2442×10^6 kWh.

The early success of the supply industry in India was due to private enterprise. Immediately after independence, the new Government enacted the Electricity (Supply) Act, 1948, to stimulate development of all power resources of the country as national assets. Autonomous bodies were set up in the different States for the conservation, development and proper working of these sources and to operate public utilities. Thanks to this new structure, it has been possible to meet the ever-increasing demand and to provide for continuous extensions of the nation-wide distribution network.

We are still dependent on a mediaeval economy, where the output of work is derived from human labour, animal power and non-commercial sources of energy such as wood, cattle-dung, charcoal, etc. In the United States, the annual consumption per head is 4 MWh; in Britain it is 2 MWh; in India it is only 0·04 MWh; the average annual consumption of electricity per head of population for the whole world is 0·6 MWh. This is an indication of the leeway the country has to make up (Table 2). The energy consumption of the five zones into which the States have been grouped to facilitate co-ordinated zonal development is shown in Fig. 1.

Plans

The task of drawing up an overall programme of power development on a national basis under the different Five-Year Plans, the first of which commenced in April, 1951, was vested in a Planning Commission. By and large, generation, transmission and distribution of electric power in India are the responsibility of the various State Electricity Boards who draw up their own programme of development. These plans are co-ordinated by the Ministry of Irrigation and Power through the Central Water and Power Commission to determine overall priorities for the allocation of foreign exchange. The Commission is also responsible for co-ordinating the programme with those of other sectors of economy such as industry, mining and transport.

Two Five-Year Plans have already been completed and the

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Table 2

COMPARISON OF ENERGY CONSUMPTION AND RESOURCES

Country	Population	Energy consumption			Non-replenishable (capital) energy sources					Replenishable sources	
		Total	Electric							Water	
			Total	Per head	Coal	Peat	Oil	Oil shale	Natural gas	Potential	Installed
	$\times 10^6$	MWh/yr $\times 10^6$	MWh/yr $\times 10^6$	kWh/yr	MWh $\times 10^9$	MWh $\times 10^9$	MWh $\times 10^9$	MWh $\times 10^9$	MWh $\times 10^9$	MW $\times 10^3$	MW $\times 10^3$
India	400	1 200	15	38	1 800	—	—	0·17	—	40	0·8
Britain	52	1 750	104	2 000	290	0·013	—	—	—	0·5	0·37
United States . .	144	8 800	730	4 100	2 230	40	20	620	105	100	18
Soviet Union . .	210	4 400	230	1 100	2 900	230	272	2·5	10	60	1·7
France	45	590	58	1 300	42·5	605	100	2·5	—	4·5	4·5
Norway	3·5	100	25	7 000	—	—	—	—	—	7·5	2·9

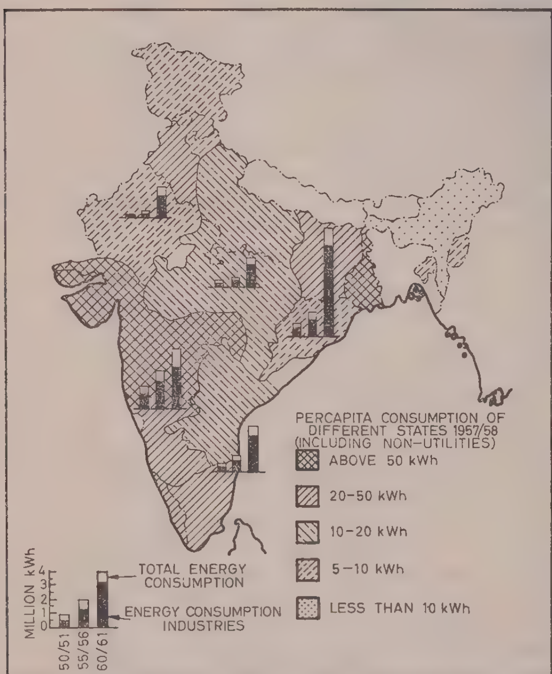

Fig. 1.—Trends in electricity consumption in various zones.

third has just been started. During the two Plans, generation and consumption have more than doubled, as compared with an increase in agricultural production of more than 33% and industrial production of 70%.

At the beginning of the First Plan in 1951, the total installed capacity was 2 300 MW, being comprised of 600 MW in the public sector and 1 700 MW in the private sector (including industrial installations with private generating plant). The capacity added during the First Plan period was 1 100 MW, bringing the total installed capacity to 3 400 MW.

The Second Five-Year Plan (1956–61) provided for a target addition of 3 500 MW in the installed generating capacity of the power plant in the country, comprising 2 900 MW in the public sector, 300 MW in the private sector and 300 MW in privately-owned industrial establishments. The target of 3 500 MW was made up of about 2 100 MW of hydro-electric and 1 400 MW of thermal power plant. The actual achievement has fallen short of the target by 1 100 MW, but the number of towns and villages electrified has increased from 3 700 in 1950–51 to 19 000 in 1960–61.

During the present Plan, emphasis is laid on the establishment of capital industries which will make the country's economy self-sustaining and self-developing, namely steel, heavy machine building plant, foundry forge, coal-mining machinery plant, heavy structural plant, heavy plate and vessel works and heavy machine tool factories. In view of the prospect for the development of other industries which they hold out, the demand for power during the Third Plan will increase substantially.

It is proposed to increase the total installed generating capacity from 5 800 MW at the end of the Second Plan (1961) to 11 800 MW at the end of the Third Plan (1966) (see Table 3).

Table 3

POWER PLAN

Plant	Generating capacity at the end of			
	1951	1956	1961	1966
	MW $\times 10^3$	MW $\times 10^3$	MW $\times 10^3$	MW $\times 10^3$
Hydro-electric . .	0·56	0·94	2·1	4·75
Steam	1·6	2·27	3·45	6·5
Oil	0·15	0·21	0·25	0·25
Nuclear	—	—	—	0·3
Total	2·31	3·42	5·8	11·8

The programme includes nuclear power generation of 300 MW. It is expected that 15 000 additional towns and villages will be electrified during the Third Plan period, bringing the total to 34 000.

The Hoffman Mission Report drew particular attention to the power difficulties experienced in every part of India and the impressive programme drawn up for industrialization, railway traction and rural electrification under the Third Plan. The target of $11{\cdot}8 \times 10^6$ kWh of electricity output by 1965–66 may, therefore, prove to be a gross under-estimate; the demand for electrical energy by 1965–66 may be in the neighbourhood of 14×10^6 kWh.

In an under-developed economy the 'take-off' to a large extent is determined by the quantum of power availability. Power shortage in almost all regions continues to affect the economy and there can be no two opinions about the need for power availability to be ahead of demand. An encouraging feature has been that, once power is available, demand exceeds expectations.

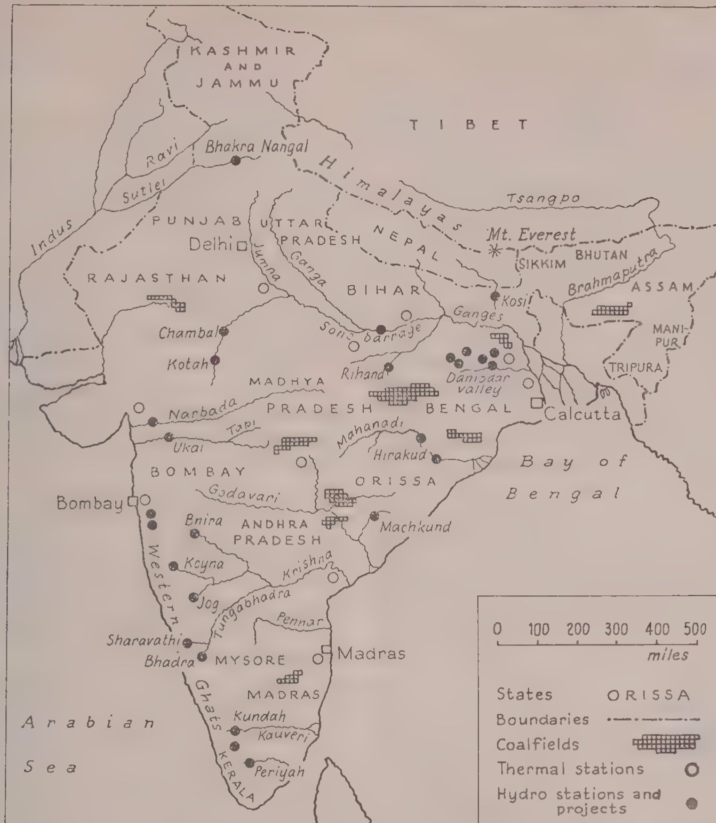

Fig. 2.—Energy sources.

Where the Energy Comes From

Sources of energy are plentiful, both non-replenishable (capital) and replenishable (current) (see Fig. 2).

Water.—The rivers in India come under two broad categories, those exclusively rain-fed, and those both rain- and snow-fed. The snow line in India ranges between 14 000 and 16 000 ft. Owing to seasonal rainfall (June to September), the former groups of rivers are characterized by heavy discharge during the monsoon months, but this dwindles to a mere trickle during the summer. Even in the latter group of rivers, which are of Himalayan origin, the perennial snowfeed reduces the variation of the river but slightly. Hydro-electric power schemes in India therefore depend for their technical and economic feasibility on reservoirs placed wherever there are favourable sites. A further limitation is set by irrigation, which overrides all other considerations. Taking all these limitations into account, the Central Water and Power Commission has assessed the water-power potential to be 40 000 MW at 60% load factor, or about $210\,000 \times 10^6$ kWh annually, equivalent to 150×10^6 tons of coal.

In addition, there are resources of the same order of magnitude located in the Himalayan foot-hill regions—Nepal, Sikkim and Tibet—which can conceivably be utilized to the mutual benefit of these countries and India. The most noteworthy is the power potential of the great U-bend of the Brahmaputra just before it enters India from Tibet. The river, with a minimum unregulated flow of the order of 30 000 cusec, drops over 8 000 ft in a sharp 125-mile U-bend. A relatively short 11-mile headrace tunnel would permit the utilization of a head drop of 7 500 ft, thus constituting, without reservoir regulation, the greatest concentration of water power (about $130\,000 \times 10^6$ kWh per year) anywhere in the world.

Coal.—The known resources of coal in India, assessed at $120\,000 \times 10^6$ tons, are localized in West Bengal, Bihar, Madhya Pradesh and Andhra Pradesh. Much of the coal is of inferior quality. The economically transportable low-grade coal has been estimated at $40\,000 \times 10^6$ tons.

Semi-bituminous and anthracite coal best meet the requirements of power generation, although quite low-grade coal can be effectively burnt. But transport of such coal to generating stations would not be easy. Pit-head power stations are eminently suitable for the loads of Bengal–Bihar coalfield areas. With the establishment of large washeries providing coking coal for steel plants, huge quantities of middlings and reject coals will be available which could be utilized for generation of power.

Oil and Gas.—The known resources of natural gas and oil are at present limited. Results of recent exploration for oil and gas have, however, raised hopes, but it has to be expected that these would be primarily required for road, rail and air transport and to a very limited extent for generation of power, mostly in isolated places.

Nuclear Power.—Our water and coal reserves are concentrated in the eastern part of the country, whereas its west coast is famous for its deposits of monazite sand. India has, therefore, to install some nuclear power stations in places far remote from coal reserves and water-power sites. While adequate reserve of

uranium ore has been assured from Bihar and Rajasthan, India is particularly rich in its thorium reserve (500 000 tons), which is available in abundance.

India's nuclear power programme is based on thorium and this programme will therefore have to be developed in three stages:

(*a*) The first will utilize reactors fuelled by natural uranium, producing electricity and plutonium (Pu 239) as a by-product.

(*b*) The second will use plutonium (Pu 239) with natural uranium in fast breeder reactors or with thorium to produce uranium 233.

(*c*) The third-stage reactors will, however, run on thorium with Pu 239 or thorium-uranium 233 cycles. This is the stage when probably cheap and abundant power can be obtained.

The Atomic Energy Commission has initiated the first two stages, so that the country can soon get nuclear power from its abundant resources of thorium. As economic operation of nuclear power stations necessitates a high load factor, three regions, which have fairly large electrical grids and heavy-industrial potentialities but are far from coalfields, have been chosen in Western, Northern and Southern India for nuclear stations.

Factors affecting choice of schemes for power generation include finances from foreign sources. The foreign-exchange component of coal-fired power stations is two or three times that of hydro-electric stations, while nuclear stations require still more. It is thus expected that hydro-electric power backed by coal-fired power stations will continue to be predominant in India's programme for many years to come.

Where the Energy Goes To

Prior to independence, rural areas were neglected altogether because of the meagre return on the investment. With the initiation of Five-Year Plan programmes, the importance of electric power for a balanced economic development of the country has been duly recognized.

Iron and Steel.—The Government have established three mills in the public sector at Durgapur, Bhilai and Rourkela in collaboration with British, Soviet Union and German combines for production of one million tons each per annum initially and $2\cdot5 \times 10^6$ tons ultimately.

Ferro-Manganese.—India has large deposits of manganese ore, the primary raw material for ferro-manganese which is exported as such. Processing of manganese ore into ferro-manganese, in addition to meeting the requirements of the country, would boost foreign-exchange earnings.

Aluminium.—Aluminium is a metal of basic importance to the economy of the country. Its consumption will increase because of the increased demand for s.c.a. conductors for electric power transmission and other industrial applications. Known bauxite deposits in India are estimated at 250×10^6 tons.

Fertilizer (Nitrogenous and Phosphatic).—The production of nitrogenous fertilizers will continue to increase at a rapid rate and four new fertilizer projects have been proposed during the Third Plan.

Cement.—Cement is a basic material for construction. The Second Five-Year Plan envisages production target of about 11×10^6 tons per year.

Colliery Electrification.—One prerequisite for realizing the target of over 90×10^6 tons of production per annum under the Third Five-Year Plan is electrification of collieries and power to meet the expansion plan.

Railway Electrification.—Electrification of railways will conserve metallurgical coal by using power from pit-head low-grade-coal-fired power stations. Total route and track lengths of the electrified sections in the Indian railways were about 250 and 550 miles respectively at the end of the First Plan period. Under the Second Five-Year Plan there is a programme of track electrification of 826 miles on the 25 kV a.c. single-phase 50 c/s

Table 4

Characteristics of Generating Plant

Plant	Capital cost	Running cost	Output	Availability	Usual type of load	Time to start	Response to varying load	Location	Maximum size of unit	Waste
	R/kW $\times 10^3$	nP/kWh	kWh/yr/kW $\times 10^3$	%		min			MW	
Conventional	1	2·5	8	80–90	Base	120–200	Poor	Influenced by fuel and cooling water	300	Ash and flue gas
Nuclear ..	2·5–4·5	2	8	80–09	Base	120–200	Very poor	Influenced by safety considerations and cooling water	100	Radioactive products
Gas turbine ..	1	3	8	80–90	Peak or standby	15	Good	Anywhere	50	—
I.C. engine ..	1	6	8	80–90	Peak or standby	10	Good	Anywhere	10	—
Hydro-electric	1–2	0·5	1–8	10–90	Peak or base	10	Very good	Topographical	100	—
Tidal	1·5–3	0·5	5	30	Fortuitous	10	Very good	Topographical	100	—
Wind	1	0·5	3	20	Fortuitous	10	Fair	Topographical	1	—
Solar	6	0·5	2	20	Fortuitous	10	Fair	Sunny climate	1	—

From the point of view of energy consumption, industrial load is the most important category, followed by domestic and commercial load and then irrigation. This pattern is not likely to change significantly.

The existing important industries are iron and steel, ferro-manganese, aluminium, fertilizer and heavy chemicals, jute, textile, cement, paper, refractories, etc., besides a considerable demand for lift irrigation, track electrification and tea plantations.

Table 5

Relative Power Consumption, 1959–60

	%
Domestic	11·1
Commercial	6·2
Agricultural (mainly irrigation) ..	5·9
Industrial	68·3
Other purposes	8·5

Table 6

INSTALLED CAPACITY AND ELECTRICITY CONSUMPTION IN VARIOUS INDUSTRIES IN 1960

Industry	Total number of factories	Installed generating plant capacity, April, 1960	Power purchased from public utility electricity undertakings	Used in the industry inclusive of self-generation	Index of usage (base year 1949)
		MW	kWh $\times 10^6$	kWh $\times 10^6$	
Aluminium (primary)	6	13	336	410	418
Cement	27	122	321	834	363
Chemicals	35	40	204	324	601
Collieries	148	64	256	401	178
Cotton textiles	337	124	1 761	2 059	182
Fertilizers	4	81	54	404	1 348
Gold	1	5	116	116	—
Iron and steel (primary)	6	298	700	1 289	—
Jute	86	26	512	572	202
Paper	24	77	147	381	228
Sugar	105	72	22	136	333
Other industries	117	15	460	504	—
Total	896	937	4 889	7 430	—

system, giving priority to those sections considered necessary for dealing with the heavy steel-mills traffic.

Tea.—Tea is one of the few major items that earn foreign exchange. The tea industrialists are eager to change over to electricity, not only for processing but also for drying. The unique feature of this industry is that the extra water during monsoons synchronizes with the tea demand, for it is the rain that both brings out the tea leaves and swells the streams.

Review of Power Generation Developments

(*a*) Hydro-Electric Generation.

Water power stations are very attractive from the national standpoint. Where economic sites are available, the first choice is on them.

Such development may be roughly divided into seven well-marked regions, namely Bombay, Madras, Mysore, Uttar Pradesh, Madhya Pradesh, the Punjab and West Bengal-Bihar-Orissa (Fig. 1). Some hydro-electric installations have no relation to irrigation or to thermal generating stations. In others, power is an adjunct of gravity irrigation and the hydro-electric installation is, or will be, a constituent of an extensive Grid system including one or more thermal stations.

Bombay.—The early sizeable hydro-electric schemes implemented were three stations built by Tatas in the Western Ghats with a total installed capacity of 235 MW, all connected to a Grid system augmented by thermal power with two units of 50/62·5 MW at Trombay near Bombay.

The Government has recently undertaken the Koyna hydro-electric-cum-irrigation project. This comprises the construction of a 207 ft-high dam across the River Koyna, a major tributary of the River Krishna, to impound $36\,000 \times 10^6$ ft^3 of water above dead storage.

Mysore.—The most important project is at Jog Falls on the River Sharavathi—named after Mahatma Gandhi—with an installed capacity of 120 MW. Further extension of the Sharavathi Valley project has recently been undertaken. The power house will ultimately accommodate 10 sets of 129 000 hp impulse turbines working under a head of 1 525 ft. Each turbine will be coupled to an 89 MW synchronous generator with a projected ultimate installation of 890 MW.

Madras.—In 1924, the Government of Madras embarked on an electrification programme and developed five major hydro-electric schemes, the Pykara (the highest-head plant—3 000 ft—in the British Commonwealth), Mettur, Papanasam Moyar and Periyar.

The Periyar scheme utilizes the waters of Periyar Lake in Kerala State. It is now in operation and provides 35 MW (first stage). The second and third stages will follow rapidly, bringing the total accession of new power to 105 MW. In addition to these single- and multi-purpose schemes, the multi-reservoir Kundah Project (180 MW) under Phase 1 has now been completed.

The large water-power potential in the southern portion of the Western Ghats in this region can be harnessed by mutual collaboration of these States, thus offering the possibility of the development of a regional Grid, with the prospect of inter-connection between Andhra, Madras, Mysore and Kerala States which is in the offing.

Punjab.—The largest multi-purpose project in India, the Bhakra-Nangal Project, now nearing completion, is a joint enterprise of the States of the Punjab (Patiala and East Punjab States Union) and Rajasthan. The Bhakra dam is located across the Sutlej River in the Indus basin in a natural gorge before the river enters the plains. The dam, now nearing completion, will be 760 ft high and will have a storage capacity of $6 \cdot 8 \times 10^6$ acre-ft. The left-bank power house, already in partial operation, will have five 90 MW water-wheel generators. The right-bank power house will have five more units of the same rating. An irrigation-cum-power channel is taken from the Nangal barrage, five miles downstream of the main Bhakra dam. Two low-head power stations, each with two 24 MW units, have been constructed on the channel at Gangwal and Kotla.

Uttar Pradesh.—The course of the Ganges Canal, as it flows towards the south, passes over a series of 13 falls varying in height from 7 to 10 ft. In 1926, the Government undertook the development of the canal as a source of electrical energy and developed eight canal power stations totalling 17 400 kW. The Sarda Canal Hydro Power Station has recently been built at Katima with an installed capacity of 48 MW.

The Rihand Dam Project, nearing completion, comprises a dam 271 ft high and 3 000 ft long located across the Rihand River near Pipri village. The power house will have six generating sets of 40 MW each. The project will further provide irrigation for $1 \cdot 4 \times 10^6$ acres of land in Uttar Pradesh and about half a million acres in Bihar.

Madhya Pradesh.—The Madhya Pradesh will largely have to depend upon the thermal schemes. The water potential available at the Chambal, an inter-State river which runs partly in Madhya Pradesh and partly in Rajasthan, is being exploited.

West Bengal–Bihar–Orissa.—This important region with a vast industrial potential comprises West Bengal, Bihar and the major part of Orissa above the Mahanadi River. The central and southern parts are rich in coal, iron, mica, copper and bauxite.

Progressive growth of thermal power installations at Calcutta (435 MW) constituted the major power development in this region till the post-war period, when the Damodar Valley Project covering the southern portion of West Bengal and Bihar and Hirakud Project in Orissa were taken up. At present the Damodar Valley Corporation have 479 MW of installed capacity in operation of which 375 MW accounts for the installed capacity in the thermal power stations at Bokaro and Durgapur and 104 MW is obtained from the hydro-electric installations in Maithon, Panchet and Tilaya.

A hydro-electric power station in the foot-hills of the Himalayas on the Jaldhaka River is now under construction.

In Orissa, the multi-purpose Hirakud Project with an installed capacity of 123 MW at the main dam has already been completed. The dam has been constructed to control and regulate the Mahanadi (an east-flowing river originating in Central India) for irrigation and power. This is the longest dam in the world: 15 748 ft long with a storage capacity of $6 \cdot 6 \times 10^6$ acre-ft.

The trend in the various States has been towards interconnection of their important hydro-electric and thermal generating stations, but there has been no significant expansion of regional Grids across State boundaries, except in the cases of Damodar Valley, the Bhakra-Nangal and the Chambal areas, where there are inter-State developments of multi-purpose schemes.

(*b*) Coal-Fired Steam Generation.

The interconnection of power stations and the formation of regional Grids during the post-independence period have led naturally to the adoption of greater unit sizes. The rate of growth of unit sizes is exemplified by the system of the Damodar Valley Corporation.

Late in 1953, the Corporation placed in service three 50 MW units at its Bokaro station; in 1960–61 three 75 MW units, one at Bokaro and two in the new Durgapur station; in 1964 two 140 MW units will be placed in service at the new Chandrapura station. The 75 MW and 140 MW units will follow the single-boiler single-turbine generator bloc concept. Increases in the initial steam pressure and temperature have kept pace with the increases in unit sizes.

All these power stations sited in the coalfields of Bengal and Bihar are designed to burn low-grade run-of-mine and slack coal, washery rejects and middling coals.

Under the Third Five-Year Plan a thermal power station, now under construction at Bandel near Calcutta, will have four units of 75 MW.

In South India, which is predominantly a hydro-electric area, the Neyvelli thermal station with 5×50 MW sets is now under construction. This is the first run-of-mine lignite-fired power station in India.

The task is at present chiefly to devise ways and means for utilizing inferior fuel—coking and non-coking as well as lignite—with a view to conserving the more valuable resources. Stations built since 1945 generally burn inferior fuels.

Pulverized-fuel firing in dry-bottom boilers is employed exclusively for all units of the Damodar Valley Corporation. This is by no means a trouble-free operation. Erosion by abrasive flyash of evaporating and secondary superheater tubes is one of the problems, while flyash disposal is just as great in India as in any other country. Cement manufacturers can take some ash for low-grade cement, provided that it is sharp and possesses good pozzolonic properties. However, the lack of rail and road facilities precludes, for the foreseeable future, any considerable commercial market for ash. Coals of the Damodar Valley contain ash high in refractory composition and low in halogen—properties not conducive to fluidity at low combustion temperature. Laboratory experiments suggest that lower fusion temperatures are possible if dolomite is introduced into the coal stream.

The responsibility for successfully burning the high-ash coals will rest principally with the generating authorities, and in future foreign boiler builders will be asked to share the risks of developing successful designs rather than absorbing them outright. The Central Fuel Research Institute will be encouraged to carry on research at laboratory, pilot-plant and full-scale station levels.

The new boilers for our pit-head power stations are designed to utilize pulverized fuel, coke-oven gas and heavy residual fuel, as most of them are located near steel plant or coke-oven plant sites. The boiler control is designed in such a way as to enable the units to operate under automatic control with gas or pulverized coal. The heavy-oil-fuel burning facility is provided for stabilizing the fire at light loads and for bringing the boilers up to partial pressure after protracted shut-down.

The collection of flyash in combination mechanical-electrostatic dust collection is no longer avoidable for large boilers burning pulverized coal in dry bottoms. Gone are the days when civilized communities submitted to ash baths.

The use of reheat for units of less than 62·5–75 MW in localities of low fuel cost is subject to special study. The capacity over 75 MW at which reheat shows an advantage depends on capacity factors, fuel cost, availability of skilled operating personnel and costs of turbine and boiler. The fact that reheating has not been adopted so far must be attributed to the general conservatism and absence of need for large single units where there is inadequate interconnection.

As our rivers in the mine fields contain so little water in the long dry season, it is necessary to resort to cooling towers. The massive hyperbolic natural-draught tower so popular in cool and humid England is not suited to the hot, dry Indian climate. The multi-cell mechanical induced-draught tower having a concrete shell and fill better meets the Indian condition.

Transmission

The highest transmission voltage in India at present is 132 kV. A few lines now in the initial stage of operation are insulated for 230 kV. Such lines interconnect large hydro-electric or pit-head thermal power stations and a remote load centre.

Overhead Lines.—The transmission voltages in common use in India are 132, 110 and 66 kV and the sub-transmission voltages are 11 and 33 kV. At and above 66 kV, galvanized or black latticed steel towers are common; 11 and 33 kV lines are borne on wooden poles, rail poles and, very rarely, on reinforced-concrete poles.

India is a vast country. The design conditions for transmission towers vary through a wide range from one region to another. The wind-loading varies from 15 lb/ft^2 for Central India to 30 lb/ft^2 for coastal and hilly regions. It is to be noted that the worst wind load does not occur at times of minimum temperature, when the conductor stress is high, but in summer, when sudden squalls of short duration with a sudden drop in temperature may occur (Fig. 3). During the low-temperature period the wind load is relatively small.

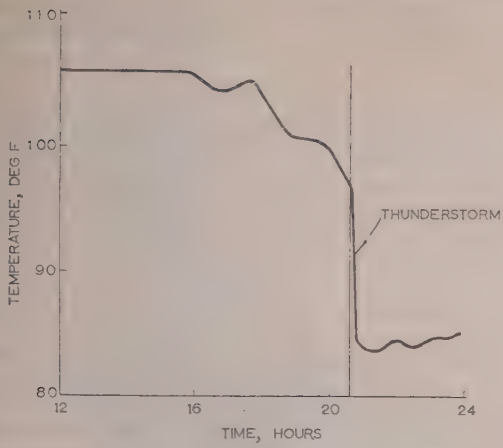

Fig. 3.—Thermograph record of temperature fall at thunderstorm observatory.

Considerable economy can be effected by dividing the country into zones of wind pressure. The worst load conditions for each zone must have specific reference to the regional climatic condition, the worst wind load being taken to occur at the actual temperature of each zone. Considerably increased tension in the line construction can thus be allowed so that the lines may be stressed to a much reduced sag, with consequent economies in support heights.

When the maximum wind occurs at a temperature higher than minimum, the conductor length under stringing condition is

$$L_2 = L_1 - (T_1 - T_2)l/aE - \alpha\theta l$$

where L_1, L_2 = Conductor lengths.
T_1, T_2 = Tension.
l = Half-span.
a = Cross-section.
θ = Temperature.
α = Coefficient of linear expansion.
E = Young's modulus.

For British conditions, where maximum loading is at minimum temperature, the sign of the last term on the right-hand side is positive, and this makes a marked difference to the stringing condition.

The temperatures vary from 30° to 150°F in hilly areas and 40° to 140°F in the interior. Thermal ratings of transformer and feeder equipments need to be reduced considerably in view of such high ambient temperatures.

Indigenous production of towers started about ten years ago, and India has attained self-sufficiency in this respect, except those for river crossings, where the use of high-tensile steel for towers can reduce the weight by about 30% compared with mild steel.

Atmospheric lightning constitutes the most frequent cause of interruption on overhead power lines. The lines and structures are generally protected by elevated earth wires over the entire length, or at least over the substations and part of the adjoining lines. The chance of a direct stroke to one of the conductors is thus reduced, and the principal danger is from back flashovers. The insulation level selected is guided by the sparkover voltage of the terminal surge diverters.

The use of continuous earth wires over power conductors for sub-transmission lines at and below 33kV is not generally favoured.

Unearthed and unbonded overhead sub-transmission lines (11/33kV) on wooden poles with wooden cross-arms provide not only the best performance under lightning conditions but also practically eliminate the risk of shock due to leakage current. Earlier attempts at popularizing wooden supports for h.v. lines have suffered from imperfect wood-preserving techniques.

Cables.—Solid-type cable is used up to 33kV, but at or above this voltage the cables used in India are either gas-filled or oil-filled.

Transformers.—In India transmission transformers do not normally operate on continuous full load and substantial economy can be derived in capital outlay by utilizing fully the thermal capacity of transformers to meet the daily peak load.

To control distribution between parallel circuits coupled by transformers, the quadrature booster is proposed for 132kV Grids in the eastern region. There appears to be a certain amount of technical shyness about the use of quadrature boosters in our country.

Switchgear.—In some of the 132 and 33kV systems, air-blast and low-oil-volume circuit-breakers are being used. Bulk-oil circuit-breakers are still in use in large numbers with very good service records, but low-oil-volume circuit-breakers are becoming more popular. Most of the 66 or 132kV circuit-breakers are provided with automatic reclosing, in spite of the fact that there is always a risk of persistent faults.

System Operation.—The design of long-distance transmission systems is greatly influenced by voltage drop and synchronous stability.

Reactance compensation with synchronous or shunt capacitors has now been frequently adopted in our country, as the transmission of reactive power adversely affects the load-carrying capacity. Reactance compensation with series capacitors seems to be a very useful means of improving system stability, although it is still difficult to provide adequate protection against fault voltages.

To match circuit-breakers having a total break time of 3–5 cycles, protective gear is limited to (*a*) carrier-current equipment using either phase-comparison or directional-impedance measurement principles, (*b*) balanced protective devices for paralleled feeders.

Where carrier protection is not economically justified, 3-zone distance protection with various refinements to maintain stability during phase swinging is in common use in conjunction with low-speed protective devices like induction relays for back-up or directional purposes.

Distribution

In the field of distribution, economy and efficiency are paramount. The main backbone of higher-voltage rural distribution is the 11kV 3-phase supply, but most spur lines therefrom (except for relatively heavy loads) are single phase. The conductors are s.c.a. or all-aluminium, although in a very few cases where the load is small, galvanized-steel conductors have also been used. There are a few experimental lines with single conductor and earth return.

Considerable economy is being exercised in the design and construction of rural distribution lines by use of indigenous material, uniformity of construction practice and the relaxation of regulations, with due regard to safety.

The major relaxations of the Indian Electricity Rules are the reduction of the factor of safety of metal and wood supports, lowering of ground clearance in rural areas, omissions of guards between high- and low-voltage lines, and restricted use of safety and protective devices such as caution boards and anti-climbing devices.

The application of wooden poles goes with planned afforesta-

tion. Experiments on jointed wooden poles are also being carried out. Combined use of high- or low-voltage rural electrification lines and open-wire P. and T. communication circuits is being made to minimize the capital cost of rural distribution.

In rural areas a co-ordinated use of auto-reclosers with fuses has been satisfactory. Good results have been obtained by connecting transformers solidly in groups protected by fuses or auto-reclosers.

Industry

Immediately after the Second World War, the scarcity of power plant and equipment all over the country made it clear that India's power-development programme might be seriously retarded, if not completely stopped, without some home manufacture of plant and equipment. Several British organizations have been manufacturing light and medium electrical plant through their respective subsidiaries in India, or in collaboration with Indian companies.

A heavy electrical plant factory has been started at Bhopal. It is already in partial operation. When completed, it will make transformers up to 400 MVA and 220 kV, circuit-breakers up to 220 kV and 7 500 MVA, hydraulic turbines and generators up to 150 MVA, steam turbines and generators of 60 MW and above, synchronous capacitors up to 1 500 kVA. Negotiation is already afoot for the establishment of two more heavy electrical works in the public sector under the Third Five-Year Plan. There are ample opportunities for British electrical firms who can manufacture in India.

Research

The Central Water and Power Commission has been entrusted with the setting up of an organization with laboratories to

(a) Investigate economic utilization of energy resources.
(b) Effect technical efficiency and economy in the supply industry.
(c) Promote the manufacture of equipment with indigenous resources.

The Future

When Lenin said that 'Electricity plus Soviet is Communism', he stressed the necessity of placing horsepower in the peoples' hands, before a target of industrial production could be achieved.

India, similarly, cannot thrive unless strong emphasis is given to the role of electrical energy in raising the standards of living of the Indian people. Power supply and distribution must continue to grow and expand.

The major problems of energy production have certainly not all been solved. Those who are engaged in the field of power engineering in India can rest assured that the future holds much to keep them interested.

India today offers to the power engineers almost a virgin soil. The future problems will be great, but enthralling and stimulating.

DISCUSSION ON 'THE LOGICAL DESIGN OF ELECTRICAL NETWORKS USING LINEAR PROGRAMMING METHODS'*

NORTH-WESTERN SUPPLY GROUP AT MANCHESTER, 22ND NOVEMBER, 1960

Mr. L. W. Campnett: The scarcity of information on system design techniques, as against system analysis, is very evident and not unexpected. The acceptance of the technique described by the author is dependent on its ready understanding by system design engineers: for obvious reasons he has had to assume some knowledge of linear programming on the part of his readers, but I think he may have over-estimated this aspect.

Referring to Section 2.1, I would include items (b) and (c) as matters of opinion, which means that cost is the sole remaining condition for linear-programming application, subject to whatever restrictions may be imposed by (b) and (c), in the opinion of the designer.

In Section 2.2, with regard to item (c), I doubt the statement that the reinforcement of existing subtransmission networks by superimposed transmission networks is likely to arise to the extent that there would be any advantage in linear programming. Five or six associated reinforcement points would extend over five or six years, during which time changed conditions due to bigger or smaller loads, or precluded line or cable routes, could very well materialize and nullify the practical application of the study.

What limitations had the author in mind in regard to the design equations?

How would the three-transformer feeder supplying two groups of three substations, which might well be the intuitive approach, compare with the results of Example 1? There would be a saving in substation costs and also an additional advantage of reduced switchgear.

With regard to Example 2, which is an interconnected system at both 132 kV and 33 kV, the study considers only interconnection at 33 kV. Much more extensive 132/33 kV interconnected systems are in existence than that covered by the example. Would not the limitations imposed by linear programming restrict any attempt to design on this scale and, therefore, would not the intuitive approach, apart from any practical considerations, be the only way?

Much further work has to be done before linear-programming techniques can be readily accepted as a system design tool. Is the author undertaking any further studies?

Mr. F. V. Dakin: Before a programme can be established for the logical design of any particular network, it is necessary to determine certain broad general principles which can be used as a basis in the detailed design of all networks; e.g. it is necessary to establish the optimum number of substations for the supply of a given load, for different voltages and over varying areas of supply. Such studies should be done for both overhead lines and underground cables, for transformer feeders and for ring arrangements.

Example 1 considers the supply of 420 MVA of load by means of six substations connected in a ring arrangement. This is a particular problem which considers the details of a system which

* KNIGHT, U. G. W.: Paper No. 3138 S, December, 1959 (see 107 A, p. 306).

has already been designed inasmuch as the number of stations has been specified and also the method of connection. In an attempt to establish certain broad principles in network design, studies have already been made in the North-Western Region which indicate that the optimum number of substations for a total load of the order of 420 MVA would be four.

Since the author is breaking new ground when applying the digital computer to the logical design of electrical networks, it would have been better to have applied the computer to the basic problems before considering the more detailed aspects.

From Section 4.4 it appears from a preliminary investigation that a transformer feeder arrangement would have been more economic for the shorter transmission distances in view of the saving on switchgear costs.

In Section 10 the author states that adoption of the technique would not make the network analyser unnecessary. Programmes on the digital computer are already available for load flows and fault levels, and I feel that, whilst not underestimating the amount of work required, it will be necessary to evolve an overall programme for the digital computer which would make it independent of the network analyser.

Mr. W. Taylor: Although the author's stated intention was to consider more designs than would be possible by present methods, the technique is confined to selecting the optimum arrangement of one design. The parameters laid down for the network, together with the estimated cost per circuit inclusive of switchgear, seem to select the design effectively, and in the case of the two examples illustrated in the paper the practicable arrangements of the network are so few as to render use of linear programming technique unnecessary.

The technique produces the optimum arrangement for the final development, but the designer requires to produce a system which is capable of economic and satisfactory technical development through several stages, leaving adequate flexibility in the late stages to allow for changes in the magnitude and location of load developments.

More important to the system designer than the arrangement of one design is the comparison of designs based on different control and network conceptions, and to do this effectively it is essential that the designs be considered at more than one voltage level.

Whilst the technique is undoubtedly useful to the designers of very large and complicated networks, it does not at present offer to the designer of normal-size networks much advantage over good intuitive selection.

If the technique can be expanded to cover the comparison of principles and to take into account development in time, the system designer will have a new tool of great value and assistance.

Mr. U. G. W. Knight (*in reply*): Two principal comments have been raised in the discussion—the design of the networks was chosen before the linear-programming method was applied, and the development of networks for minimum cost over a defined period of years is required.

Network design consists in choosing both equipment ratings (current and voltage) and a topology for equipment with those ratings which will give a technically satisfactory and economic network. Ideally both the rating and topological questions should be considered simultaneously. Ways of doing this except by the use of intuitive reasoning for the topological aspects are not known to the author and, in addition, equipment ratings are, in practice, frequently standardized, and only the topological problem remains. This was the starting-point taken in the paper. In the examples quoted, therefore, it was assumed that equipment of standard ratings would be used, and that the size and number of substations chosen to be connected were reasonable from consideration of existing networks. However, an extension of the method to multi-voltage design would greatly increase its value. This development has not so far proved possible. A comparison of l.p. designs, each with differing design parameters, such as numbers and sizes of substations, circuit ratings, etc., would go part way towards solving this problem.

Some progress has been made in applying linear programming to the development of networks in time. Briefly, the reinforcement period is split into a number of time intervals, s, for each of which a set of constraint equations relating substation groups and circuit capacities are written in terms of p_{ijs}. Here p_{ijs} denotes the circuit paths available between substations i and j in time period s. These sets of equations are related by a final set of constraints

$$p_{ijs} \geqslant p_{ij(s-1)}$$

These state that a circuit provided in any interval is available in all subsequent intervals. The cost function to be minimized is

$$\sum_{i=1\neq j}^{n+m} \sum_{j=1\neq i}^{n+m} \sum_{s=1}^{s} [C_{ijs} - C_{ij(s+1)}]p_{ijs}$$

where C_{ijs} is the present worth of a circuit along path ij provided in period s. The l.p. matrix size is increased by approximately s^2 compared with the sizes quoted in the paper.

DISCUSSION ON 'DEVELOPMENT OF HIGH-VOLTAGE AIR-BREAK CIRCUIT-BREAKERS WITH INSULATED-STEEL-PLATE ARC CHUTES'*

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 6TH FEBRUARY, 1961

Mr. D. A. Muret: The authors make passing reference to the metal-splitter-type arc chute, but perhaps have not done it full justice. Whilst it is true that this type of chute introduces problems at voltages of 6·6 kV and above, it has proved a very efficient design for voltages of 3·3 kV up to interrupting capacities of 250 MVA.

Section 5.1 gives some observations on the effect of electrode materials on arc velocity. The curves in Fig. 6 show that the arc will run faster on copper than on steel, whereas in the test the reverse is stated. This anomaly is probably explained by the currents used for the different tests. At very high currents the arc runs very quickly in any case, and it is only on low currents that any difference in electrode material will be important. Since a puffer is used to assist low-current interruption, there would not seem to be any obvious advantages of either steel or copper.

In Section 4.4 it is stated that the arcing contacts are of the blow-off type. Whilst it is obviously very desirable that the

* Fay, F. S., Thomas, J. A., Legg, D., and Morton, J. S.: Paper No. 2746 S, November, 1958 (see 106 A, p. 381).

initial arc should be drawn between the arcing contacts in such a way that the electromagnetic forces driving it in the chute are high, nevertheless it is most undesirable that the arcing contacts should actually blow off. Such an action would undoubtedly increase the burning on the main contacts and have a deleterious effect on the transfer of current from the main contacts to the arcing contacts.

I agree with the authors that the most severe duty for an air circuit-breaker is the breaking of asymmetrical currents. Owing to the very heavy current suppression which occurs with this type of circuit-breaker, the most onerous point on the wave at which the contacts can separate is probably shortly after the current zero, when going into a major loop. This point of contact separation allows the full peak current to appear in the chute before the arc is long enough to effect any suppression.

A high-voltage air circuit-breaker, operated at high currents, carries quite a large post-arc current. Experiments we have made on 15 kV circuit-breakers show an arc resistance of something less than 1 kΩ, resulting in post-arc currents of about 10 A.

Mr. J. S. Cliff: The development of the air-break circuit-breaker has depended very much upon the materials which are available, particularly for the construction of the arc chutes. In the United States, where for many years there has been a large demand for oil-less circuit-breakers, thus providing a greater incentive to develop the air-break design, special materials played a large part in the evolution of ratings exceeding those of the circuit-breaker described by the authors. One maker used a specially moulded phosphor-asbestos mixture, while others, in conjunction with porcelain manufacturers, developed ceramic plates which would resist the high thermal shocks during arcing, and produce no carbon or gases during operation. Arc chutes using such materials need external magnetic circuits and exciting coils, but no great difficulties were met in providing suitable contact systems. In this country materials of as good quality are not readily available and are very expensive owing to the small demand. The authors have used another new material which is available here, and it has enabled them to adapt the old principle of embedded metal plates for arc movement, as was done on arc-control pots for oil circuit-breakers on several very early designs. This has eliminated the external magnetic circuit and exciting coils, but it is still a very expensive and bulky arc-chute construction. The non-tracking characteristics of Perspex have also proved useful.

The authors show that considerable arc energy is liberated within the chute; this gives an internal pressure which stresses the side plates. It would be interesting to know whether pressure measurements were made.

The asymmetrical short-circuit test is undoubtedly the more onerous, and present British Standards specify a 50% d.c. component value. Is that figure high enough for this type of circuit-breaker?

Mr. I. G. Edwards: It has been stated that the size of air-breaker equipment is somewhat larger than the oil-break equipment. For distribution purposes this means that larger and therefore more costly substations will be required, thus offsetting any savings in circuit-breaker costs. Are there any special requirements with regard to substation ventilation?

If circuit-breakers of this type are to be used for normal distribution purposes (i.e. in comparatively small substations) the side effects of large flash and high noise will have a detrimental psychological effect on operating personnel, since the operating engineer will be fairly close to the equipment.

Do the authors expect the main contacts of their circuit-breaker to have better operating characteristics than oil-circuit breaker contacts for similar duties? I have in mind the necessity, at times, of closing a ring-main circuit-breaker, probably two or three times, on to a fault in order to locate the faulty section of main.

Mr. R. W. Hankin: Since the first 11 kV auxiliaries were installed at Willington 'B' power station fault levels have increased to the order of 500 MVA for the cases of West Thurrock and Thorpe Marsh. Two further projects being planned will require 11 kV switchgear having a 750 MVA fault rating, and yet another system will require switchgear at this same voltage, which, in certain conditions, may be called upon to 'make' on to faults in excess of 750 MVA.

In view of this trend, what, in the opinion of the authors, is the ultimate limit of rating to which 11 kV arc chutes and switchgear of this type should be developed?

With reference to 15 kV application, the Americans are usually more interested in impulse withstand as opposed to the British practice of being clearance conscious. What impulse levels do the authors consider should be expected of 11/15 kV air-break switchgear, and as no British Standard clearances are specified for 15 kV, what do they consider should be the clearances necessary to suit British requirements? Our conclusions, graphically deduced, are that such clearances should be of the following order:

Minimum length of insulator in air: 8 in.
Phase to phase in air: 8½ in.
Phase to earth in air: 5½ in.

Mr. S. Taylor: What degree of erosion is suffered by the insulation of the splitter plates? What is the life of the chutes?

Mr. H. M. Fricke also contributed to the discussion at Birmingham.

Messrs. F. S. Fay, J. A. Thomas, D. Legg, and J. S. Morton (*in reply*): The advantage of using butt arcing-contacts of the blow-off type, namely rapid transfer of the initial arc into the chute, offsets the tendency to increase burning of the main contacts during transfer. In fact, there is negligible burning at the main contacts for currents up to 40 kA, and erosion of the arcing contacts is less than for equivalent contacts in an oil circuit-breaker.

The severity of the asymmetrical short-circuit test is governed as much by the point-on-wave of contact separation as by the magnitude of the d.c. component. The present British Standard of 50% d.c. component is sufficient if the arcing period includes a major loop of current on at least one phase.

Only a few measurements have been made of pressure within the arc chute. Tests indicated that below 20 kA the pressure generated is approximately proportional to the peak current and of the order of 0·1 lb/in^2 per kA peak.

A rating of 750 MVA is a practical limit for both air and oil circuit-breakers, because symmetrical currents in excess of 40 kA entail special design. We would expect the impulse level of 11 kV air-break switchgear to be 75 kV, and of 15 kV switchgear to be 95 kV. The insulation dimensions suggested by Mr. Hankin appear satisfactory for Class-B clearances at 15 kV, but, as indicated in the paper, Class-A clearances and Class-B creepage distances are to be preferred provided that the impulse requirements are covered. Class-A clearances and creepage distances for 15 kV can be evaluated from B.S. 159: 1957.

The erosion of the arc plates depends on the current, but is very slight. The life of an arc chute in practice will probably equal the life of the gear.

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TECHNICAL AND ECONOMIC ASPECTS OF THE SUPPLY OF REACTIVE POWER IN ENGLAND AND WALES

By W. CASSON and H. J. SHEPPARD, B.Sc., Members.

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SUMMARY

The paper discusses some problems of supplying reactive power in the transmission and distribution systems of England and Wales.

The overall reactive-power requirements of the inductive loads of consumers and the shunt and series inductances of the system are reviewed and their effect on generator characteristics is examined. Consideration is given to the problems of supplying the demand for reactive power by means of the generators, system capacitance and compensating devices, and a scheme is outlined for the effective control of reactive power and voltage. An example is given relating to the possible conditions when the system load reaches 30 GW, and it is shown that the kVAr/kW ratio at bulk supply points for the optimum loading of the generators postulated is about 0·4 (0·93 lagging power factor) at times of peak load.

Estimates are made of the extra cost of providing and operating a power-supply system to transmit reactive power as well as active power. Consideration is given to various forms of tariff adjustment for reactive-power supply, leading to a preference for separate charges for active and reactive power demands.

The advantages and disadvantages of generating reactive power at or near the load, by the consumer or by the supply authority, are discussed. It is concluded that present methods of tariff adjustment are generally effective in inducing consumers to limit their demands for reactive power to an extent which would make uneconomic the provision of additional sources of reactive power on distribution systems.

LIST OF SYMBOLS

a = Tariff demand charge, £/kW.
b = Tariff demand charge, £/kVAr.
C = Capacitor kVAr for 1 MW load.
c = Capacitor kVAr for 1 kW load.
f = Annual load factor (expressed as decimal fraction).
I_{P1} = Component of current in phase with voltage.
I_{Q1} = Component of current which lags voltage by 90°.
I_c = Current in shunt capacitor.
I_1–I_4 = Current in examples shown in Fig. 3.
i_1, i_2 = Excitation currents shown in Fig. 1.
P = Active power.
Q = Reactive power.
R = Resistance.
R_L = Resistance of load.
V = Voltage.
V_A, V_B = Voltage at points A and B.
X = Reactance.
X_{CE} = Reactance of series capacitor.
X_{CH} = Reactance of shunt capacitor.
X_L = Reactance of load.
ϕ = Phase difference.
ϕ_1–ϕ_4 = Phase differences between current and voltage V_B in examples shown in Fig. 3.

Mr. Casson is with the Central Electricity Generating Board and Mr. Sheppard is with the Yorkshire Electricity Board.

(1) INTRODUCTION

Power systems are designed to meet the requirements for both active and reactive power; whereas the former is wholly supplied by the generators, the latter can be supplied from other sources. If the reactive power required by the inductive loads of consumers were generated entirely at the point of connection, the supply authorities would be concerned only in supplying the difference between the reactive power generated by the capacitance of the system and that absorbed in the series and shunt inductances of the system. Tariffs for industrial loads could then be based only on the power demand and energy consumed. In practice this condition is not realized and the supply authorities provide both reactive and active power to their consumers. In doing this they endeavour

(*a*) To design and control the system to supply both types of power in the most economical way.

(*b*) To persuade consumers with inductive loads to supply part of their demand for reactive power, but if they choose not to do so, then to ensure that the extra cost of supplying the reactive power as well as active power is recovered in the tariff.

(2) THE SUPPLY SYSTEM AND DEMAND FOR REACTIVE POWER

The supply system of England and Wales includes a transmission network owned by the Central Electricity Generating Board, to which most of the generation is directly connected and from which supplies are given in bulk to the Area Boards. It also comprises a number of distribution systems owned by the Area Boards, which radiate from the bulk supply points and to which the remainder of the generation is connected.

The transmission network consists of a principal system at 275 kV, a secondary system at 132 kV and a few lines at 66 kV and lower voltages. Auto-transformers are used to step down from 275 to 132 kV, and double-wound transformers from 275 or 132 kV to 66 kV, 33 kV and lower voltages. All transmission transformers and most generator step-up transformers installed during the past 20 years are provided with on-load tap-changers. In the future most of the new generators will be connected to the 275 kV system and later to the 400 kV system and will be of large sizes.

The generators are connected to the system and loaded in merit order, in respect of cost of generation, to meet the changing load during the day. This method of operation and the requirements at the bulk supply points result in frequent changes in the magnitude and direction of both active and reactive power flows in many of the lines of the transmission system, although in others the flows are kept sensibly constant and unidirectional for long periods.

The circuits of the transmission system can be classified as follows:

(*a*) Those which are mainly required for bulk transfers from high-merit generators located near the coalfields to places where the local generating plant cannot meet the load requirements at peak.

(*b*) Those which are required for interconnection between centres having both load and generation and which are mainly used for

transfers at off-peak times in order to allow the most efficient generators to be used to the fullest extent.

(c) Those which are mainly required for bulk supplies to the Area Boards.

These circuits generate reactive power by virtue of their shunt capacitance and consume it by virtue of their series inductance, the magnitude of their consumption depending upon their load currents.

The distribution systems, consisting of 66 kV and lower-voltage circuits, include transformers which provide supplies to consumers at 33 kV, 11 kV, 415/240 volts and other voltages.

The reactive-power demand at the bulk supply points is that consumed by the load plus that consumed in the series and shunt inductances of the distribution system less that generated by the system capacitance and by shunt capacitors and other sources of reactive power.*

(3) CONTROL OF REACTIVE POWER AND VOLTAGE

(3.1) General

The Area Boards have an obligation to maintain the voltage at the consumers' terminals within the statutory limits. This necessitates voltage control at points on the transmission and distribution systems by transformer tap-changing, by adjustment of generator excitation or by change of reactive compensation.

The reactive power supplied by the generators is that required by the load plus that consumed, or less that generated, in the supply system. The division of this balance between generators is dependent upon the control of the voltage of the generators, which can be effected by manual operation of the exciter-field rheostats or by automatic regulators. Keeping the voltage of a generator constant means maintaining for a fixed output of active power a fixed output of reactive power. If the reactive-power demand is suddenly increased or decreased the automatic voltage regulator, if in commission, will adjust the excitation until the machine angle adjusts itself to the value corresponding to the new reactive power. The effect of this can be shown more clearly by reference to Fig. 1; this is a typical performance chart

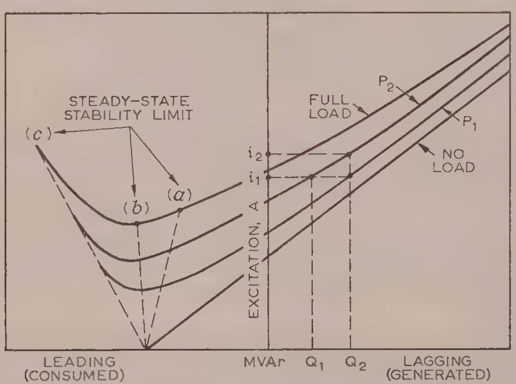


Fig. 1.—Performance chart for generator.
(a) Hand-controlled excitation.
(b) Normally inactive a.v.r.
(c) Continuously acting a.v.r.

for a generator, and it is seen that, for an active load, P_2, and a reactive power output, Q_1, an excitation, i_1, is required. If the reactive power demand is increased to Q_2 a new value of excitation, i_2, is required to maintain the same active power,

* In the paper the authors are using the convention that the power output of a generator is represented by $+P$ and the reactive power output by $+Q$ when operating at lagging power factor and $-Q$ when operating at leading power factor. In circuits where the power flow is represented by $+P$ the corresponding reactive power flow is represented by $+Q$ when lagging and by $-Q$ when leading.

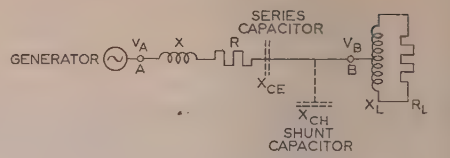


Fig. 2.—Schematic of elementary system.

but if the power is reduced to P_1 at the same time, the excitation will remain unchanged.

Fig. 2 shows a simple system comprising a series impedance, $R + jX$, between an isolated generator and the load. If the reactive-power demand on the generator increases, owing to an increase in X or decrease in X_L, and there is no voltage regulator in commission, the voltage regulation, $V_A - V_B$, will be increased, and the magnitudes of V_A and V_B and the active power will probably be reduced. The generator speed will increase until the governor effects a corresponding reduction in steam input to the turbine. With the voltage regulator in commission this would operate on the fall in V_A caused by the increased reactive demand, to bring this voltage back to normal, but there would still be a reduction in the active-power output owing to reduction in magnitude of V_B. To restore V_B to normal with no change in the active-power output, V_A would have to be increased by setting the regulator to a higher field. If V_A is kept constant, an alternative way to restore V_B to normal is to inject reactive power at point B equal to the difference in the reactive load before and after the change.

(3.2) Proposed Scheme for Effective Control of Reactive Power and Voltage

At present in Great Britain there is no automatic control of reactive power on the system. The great majority of generators have automatic voltage regulators which are kept in commission and adjusted as the load changes; the excitation of the remaining generators is controlled manually.

There are many advantages in providing some measure of automatic control of reactive power and system voltage on the transmission system. One of these is that it would relieve the system control engineer from the necessity of adjusting the reactive-power outputs of the generators to meet sudden changes in the active-power loadings—which is an important matter when the load position is changing rapidly, such as at the commencement of the morning peak. Another advantage is that when emergencies occur, such as an outage of a circuit on fault, there would arise no serious consequences such as voltage instability through the resulting increased reactive-power demand.

The following method is suggested for meeting the demand for reactive power and controlling the transmission voltage up to the points of bulk supply to the distribution system:

(a) To plan in advance the hour-by-hour optimum reactive-power outputs for the generators as they are to be operated in merit order. These outputs would be chosen with due regard to the capabilities of the generators to produce or absorb lagging reactive power without overheating or risk of instability and the capacity of the system to transmit reactive power within permitted limits of voltage regulation. The programme would include the required tappings of the generator transformers.

(b) To regulate the reactive-power outputs of the generators as planned by adjusting the settings of their voltage regulators, or their field rheostats where regulators are not in use.

(c) To use synchronous compensators, unloaded generators or equivalent devices connected at appropriate points on the transmission system, or on the lower-voltage sides of the Grid transformers, and after regulating their output by hand control to give the desired voltage levels at the points on the system where they are located, to set the automatic voltage regulators of these machines or devices to maintain those levels. These compensating devices

would have to be capable of generating or consuming sufficient reactive power to meet the difference between the reactive-power demand of the distribution and transmission systems and the planned reactive-power output of the generators under all conditions of operation. It would be necessary to ensure that there was at all times sufficient reserve of reactive output to meet an emergency. Generators connected to distribution systems would be treated as compensating devices within their known capacities to supply and absorb reactive power and would therefore have their excitations adjusted to maintain sensibly constant busbar voltage.

Table 1 shows the national conditions which could apply when the system active load reaches 30 GW at peak. It is assumed that between peak load and the minimum load (20%), the generators would be run in merit order as shown. The computed reactive power which would be consumed and generated in the transmission system is given in columns 10–12. The optimum reactive loadings of the generators are assumed to be those given in columns 13–16 [corresponding to a power factor of unity for generators connected at 275 kV with s.c.r. = 0·6–0·85 (Ref. 10) and 0·9 lag for generators at voltages below 275 kV with average s.c.r. = 0·55]. To produce a balance it would be necessary for the reactive-power demand of the load at the bulk supply points to be as given in column 17. This is seen to be 11·2 GVAr (0·93 lag) at peak, and comparison between columns 17 and 18 suggests that very little compensation in the form of synchronous compensators or their equivalent would be required if a lagging power factor of 0·93 were achieved at all loads. In practice, it is essential to provide much greater compensation than that given in column 19, because the optimum load power factor may not be achieved, and to provide for the variations which could occur in the transmission system through circuit outages. It is estimated that, under the conditions assumed in Table 1, synchronous compensators (or other compensating devices) having a range of from 3·5+ to 2·5− GVAr would be required to cover all contingencies. It will be appreciated that by adopting reactive loadings of the generators other than those given in columns 13–16, some reduction in synchronous compensators would be obtained.

The bulk-supply tariff of the Generating Board is at present based on a kilowatt demand charge plus an energy charge, no adjustment being made for reactive power. If the optimum power factor at peak load, e.g. 0·93 at 30 GW as in Table 1, is not attained, thus necessitating the provision of additional compensation on part of the transmission system, it seems equitable that the associated costs should be debited to the Area Board concerned. These costs, and also those incurred by the Area Board in transmitting the additional reactive power, would be recovered from the consumers by the application of suitable tariffs.

Table 1

CONDITIONS WHEN PEAK LOAD REACHES 30 GW

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Load	Generators								Transmission system			Optimum reactive power loading of generators				Optimum reactive power demand desired at bulk supply points =(16 + 12)	Reactive power demand corresponding to a power factor of 0·93 lagging	Compensation required = (17–18)
	Output				Maximum capacity for generating* reactive power at m.c.r.				Reactive power consumption and generation									
	275 kV	132 kV	D.V.	Total	275 kV	132 kV	Distribution voltage	Total	Series	Shunt	Total	275 kV	132 kV	D.V.	Total			
%	GW	GW	GW	GW	GVAr	GVAr	GVAr	GVAr	GVAr	GVAr	GVAr	GVAr	GVAr	GVAr	GVAr	GVAr	GVAr	GVAr
100	8	9	13	30	4·5 +	6·1 +	10·6 +	21·2 +	2·8 −	3·0 +	0·2 +	0	4·5 +	6·5 +	11·0 +	11·2 −	11·9 −	0·7 +
80	8	9	7	24	4·5 +	6·1 +	5·7 +	16·3 +	2·5 −	3·0 +	0·5 +	0	4·5 +	3·5 +	8·0 +	8·5 −	9·5 −	1·0 +
60	8	9	1	18	4·5 +	6·1 +	0·8 +	11·4 +	2·0 −	3·0 +	1·0 +	0	4·5 +	0·5 +	5·0 +	6·0 −	7·1 −	1·1 +
40	8	4	0	12	4·5 +	2·7 +	0	7·2 +	1·5 −	3·0 +	1·5 +	0	2·0 +	0	2·0 +	3·5 −	4·8 −	1·5 +
20	6	0	0	6	3·4 +	0	0	4·5 +	0·9 −	3·0 +	2·1 +	0	0	0	0	2·1 −	2·4 −	0·3 +

* Based on generating capacity in commission equal to 110% of output in column 5.

Note: + = Reactive power generated.
− = Reactive power consumed.

The deviation of the figures of columns 10, 11 and 12 are given in Table 6, Section 10.2.

The form which these tariffs should take can be properly understood only after the costs of supplying reactive power in addition to active power to consumers have been determined, and it is proposed to study this in Section 5.

(3.3) Point of Application of Compensating Equipment

It has been mentioned that the reactive-power compensating equipment could be installed either on the transmission system or on the lower-voltage sides of the Grid transformers. On the transmission system it would be connected in large units direct to 275 or 132 kV circuits or busbars, or to tertiary windings on the 275/132 kV auto-transformers. Automatic operation would be controlled by voltage-operated relays set to maintain the planned voltage levels. On the lower-voltage sides of the bulk supply transformers compensating equipment would be provided in relatively smaller units, either fixed or variable. If variable, they might be arranged to maintain voltage levels suitable for distribution requirements, and if automatically operated would reduce, or might even eliminate, tap-changing on the bulk supply transformers and provide smoother voltage control.

(4) COMPENSATING DEVICES

Reactive compensation devices may be connected in shunt or series. In general, shunt-connected devices modify the currents flowing in the circuits and can thereby reduce losses and voltage drop. Series-connected devices modify the impedance of the circuits but do not significantly alter the currents.

There are three types of compensating devices, namely

(*a*) A fixed shunt-connected unit generating or consuming a predetermined amount of reactive power.
(*b*) A variable shunt-connected unit having control features for varying the amount of reactive power or for changing from generation to consumption.
(*c*) A fixed series-connected unit which generates or consumes reactive power in proportion to the load current.

Fixed shunt-connected units comprise the shunt capacitor and the shunt reactor.

The shunt capacitor has the advantages associated with static equipment and can be installed at any point on the transmission and distribution systems or on a consumer's installation. Over a wide range of ratings the cost is approximately £2–£3 per kVAr installed and the losses have the low value of about 3 watts/kVAr. The reactive power generated depends on the voltage and frequency, and can therefore be regarded as virtually constant at most points on a supply system. Control of the amount can be achieved by switching some or all the capacitance in and out.

The fixed type of shunt reactor practically consumes a constant amount of reactive power and has a restricted field of application. A shunt reactor may be connected to a long cable to cancel out some of the reactive power generated by its capacitance, or switched to a busbar at times of light load, to compensate for part of the shunt capacitance of the system.

Variable shunt-connected units include the synchronous compensator, synchronous motor and the shunt transductor.

The synchronous compensator can be made to generate or absorb reactive power by adjustment of the excitation. This flexibility makes it particularly suitable for regulating the effective reactive-power requirements, and therefore the voltage at the point of connection, over a wide range of operating conditions. Its cost is about £4 per kVAr installed for a large unit, and the losses are of the order of 20–25 watts/kVAr. The machine has the limitations associated with rotating plant, it can supply fault current to the system and problems of instability may arise. Unloaded generators can be used in certain circumstances to serve as synchronous compensators.[11]

The synchronous motor (or synchronous induction motor) may be substituted for the induction motor in the larger sizes, such as 100 hp or over. In addition to providing mechanical power, it can generate reactive power although it is seldom economical for this to exceed 30% of the active power.

The shunt capacitor with shunt transductor combines a fixed generation of reactive power with a variable consumption, from which it is possible to obtain a net generation or consumption by adjustment of the transductor. The whole of the equipment is static. Accurate costs of this combination are not readily available.

Fixed series-connected units include the series capacitor and the series reactor.

The series capacitor is installed primarily to reduce voltage drop by compensating for part of the series inductance of the supply system. Its purpose is to modify the effective reactance of the circuit in which it is connected and its function as a generator of reactive power is subsidiary. The rating of a series capacitor is substantially less than that of a shunt capacitor required to effect a given voltage improvement, but their costs per kVAr installed are about the same. The protective devices installed on series capacitors may make them ineffective under fault conditions.

The series reactor is installed chiefly to reduce the fault level on part of the system, by increasing the supply circuit reactance.

(5) TECHNICAL AND COST STUDIES

The cost of supplying reactive power to consumers comprises the costs of generation, transmission to the bulk supply points and distribution.

(5.1) Generation

Reference is made in Section 3.2 to the need to regulate the flow of reactive power on the transmission system, and the conditions postulated when the national load reaches 30 GW indicate that, to make best use of the capacity available in the generators for generating reactive power at times of peak load, a power factor at the bulk supply points of 0·93 is desirable.

It is a matter of some difficulty to assess the additional costs which arise if the optimum power factor is not achieved. If it means simply using the spare capacity to supply reactive power without reduction of active power, the extra cost can be expressed in the increased losses in the generators. If it means that the amount of generating plant on load has to be increased to give greater kVAr/kW output, the extra cost of generation must be allowed for, and if synchronous compensators or other compensating devices are necessary, the extra cost of supplying and operating these must be taken into account. Thus the increased annual cost could vary between £0·1 and £1·0 per kVAr.

In practice, the power factor at the bulk supply points lies between 0·85 lagging and unity, and the increased cost of supplying reactive power at the point of generation of active power is small enough to be neglected in the following studies, since the bulk of the increased costs in the system lie in providing increased capacity in the transmission and distribution circuits and transformers.

(5.2) Transmission and Distribution

The transmission of reactive power as well as active power through a supply system of definite current rating causes a reduced voltage at the receiving end and a reduced capacity to transmit active power.

In the elementary system shown in Fig. 2 a current I_1, which is in phase with the voltage V_B (i.e. unity power factor load at B) will result in the voltage V_B lagging, and being slightly less than, V_A as shown at OY_1 in Fig. 3(*a*). The diagram is drawn for a circuit which has a reactance/resistance ratio considerably in excess of unity, this being typical of a circuit which includes a transformer.

If the current is altered to I_2, which is equal to I_1 but lags V_B by ϕ_2, as in Fig. 3(*b*), the voltage at B will be reduced to OY_2 as indicated by the locus of Y, and the active power transmitted will be reduced in proportion to cos ϕ_2.

V_B can be increased by using a shunt capacitor to generate part of the reactive current required by the load at B, thus altering the current transmitted through the circuit from I_2 to I_3, as shown in Fig. 3(*c*). The voltage at B will then be OY_3, point Y_2 in Fig. 3(*b*) having moved to Y_3. Alternatively, a series capacitor can be used to compensate part of the reactance of the circuit, thus reducing the quadrature component of the voltage drop from I_2X to $I_4(X - X_{CE})$, as shown in Fig. 3(*d*). Point Y_2 is then moved to Y_4.

It is now proposed to estimate the increased costs of transmitting reactive power through typical components of a supply system. It will be assumed that the rating of the circuit and the total current and losses remain unchanged, so that as the reactive power is increased the active power transmitted is

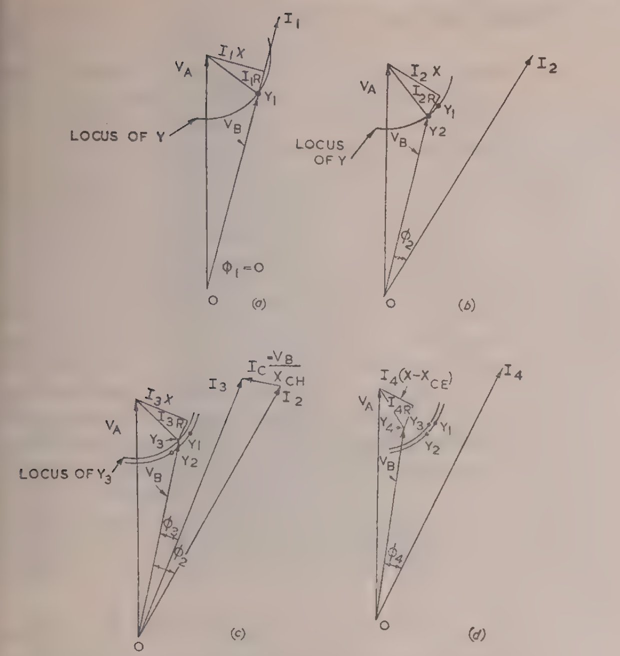


Fig. 3.—Vector diagrams for elementary system.

(a) Load current I_1 in phase with voltage.
(b) Load current I_2 lagging voltage by ϕ_2.
(c) Load current I_2 partly generated by shunt capacitor of reactance X_{CH}.
(d) Circuit reactance partly compensated by series capacitor of reactance X_{CE}.

reduced. The cost per kilowatt transmitted will then give a measure of the increased losses and capital charges associated with the transmission of reactive power. Allowance will also be made for the cost of equipment for additional voltage control. The economic merits of supplying the reactive power required by the load from local sources (in whole or in part) can then be investigated.

The typical system selected is shown in Fig. 4(a) and extends from a 132 kV power-station busbar to the point of supply to a 415-volt 3-phase consumer. Account is taken of appropriate overload ratings and security standards, and the loading conditions are such as would normally be regarded as approaching full load, i.e. the more important circuits are loaded to firm capacity.

The allowable loading on a circuit must, however, be determined by reference to acceptable limits of voltage regulation as well as temperature conditions. A permissible limit of voltage regulation of 5% under normal system operating conditions has been assumed for each of the major sections of the system, namely the 132 kV line, the 132/33 kV transformers and the feeder-transformer circuits from the 33 kV busbars to the 11 kV busbars. This implies a regulation of approximately 10% in the emergency condition of the loss of one of a pair of circuits and the consequent doubling of the load normally carried by the other circuit. Control of the voltage on the 33 and 11 kV busbars is afforded by the on-load tap-changing equipment on the 132/33 and 33/11 kV transformers respectively. While increased voltage regulation could, in practice, be provided by extending the transformer tapping range, the studies assume that the voltage variation is limited by installing series capacitors to compensate part of the circuit reactance. This hypothetical method of making a small adjustment has the advantage that the capacitor rating and cost can be varied in small steps, thus facilitating economic comparison. The studies showed that there is no difficulty in keeping the voltages at the ends of the circuits within the limits allowed.

The costs include annual capital charges, maintenance and losses. The costs of transmission losses are estimated on the basis of the C.E.G.B. tariff for bulk supplies to Area Boards, with adjustments at points remote from the 33 kV bulk-supply-point busbars. For simplicity in presentation the transmission costs are regarded as 'demand-related'. Further details are given in Section 10.1.

(5.3) Transmission System and Bulk Supply (132/33 kV) Transformers

The system is shown in the upper part of Fig. 4 and studies have been made for transmission distances of 20 and 50 miles

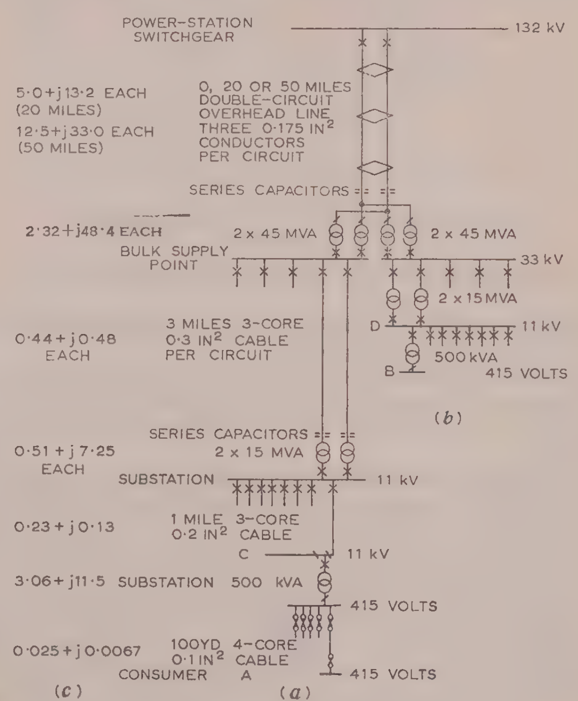


Fig. 4.—System layout forming basis of study.

(a) Distribution circuit arrangement for maximum cost.
(b) Distribution circuit arrangement for minimum cost.
(c) Impedance in ohms (transformer impedances are referred to the higher-voltage side).

and for 132/33 kV transformation at the power station. The present national average transmission distance at 132 kV is about 20 miles.

The costs for various kVAr/kW ratios are plotted in Fig. 5, in which the bulk-supply demand charge at the 33 kV busbars is taken as the datum and the 132 kV system costs are subtracted from it. The '0-miles' line indicates the cost of 132/33 kV transformation only, while the lower lines show the additional costs associated with 20 and 50 miles of 132 kV overhead line.

(5.4) Distribution System

The circuits shown in Fig. 4(a) can be regarded as typical for supplies to industrial çonsumers in England and Wales, while Fig. 4(b) gives the limiting condition where the 33/11 kV and 11/0·415 kV transformers are adjacent to the bulk supply point.

The addition of the cost of 33/11 kV transformation to the datum line in Fig. 5 gives the line of minimum 11 kV cost, D_1D_2.

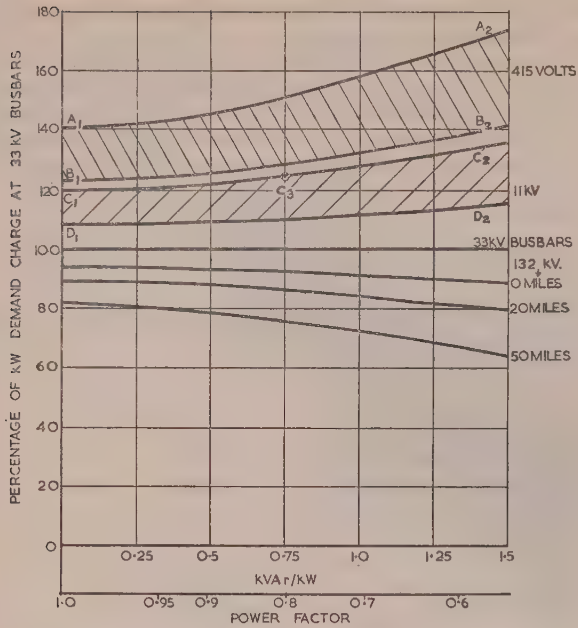


Fig. 5.—Total annual cost of supply at various parts of system.

The line of maximum 11 kV cost, C_1C_2, allows also for 3 miles of 33 kV cable and 1 mile of 11 kV cable.

Similarly, for the 415-volt system the line of minimum cost, B_1B_2 in Fig. 5, relates to the circuit arrangement in Fig. 4(*b*), while that of maximum cost, A_1A_2, relates to the system in Fig. 4(*a*).

The costs for other system arrangements which are in general use for providing industrial supplies will fall between these extremes and will therefore be within the ranges indicated in Fig. 5 for 11 kV and 415 volts respectively. For example, the costs for overhead 33/11 kV feeder-transformer circuits up to 7 miles long would not exceed those shown for cables 3 miles long.

Fig. 6 shows for various kVAr/kW ratios the percentage increase in cost over the cost for no reactive power (unity power factor). As in Fig. 5, the costs for the 132/33 kV system are shown below the datum line and the costs for the distribution system are above that line.

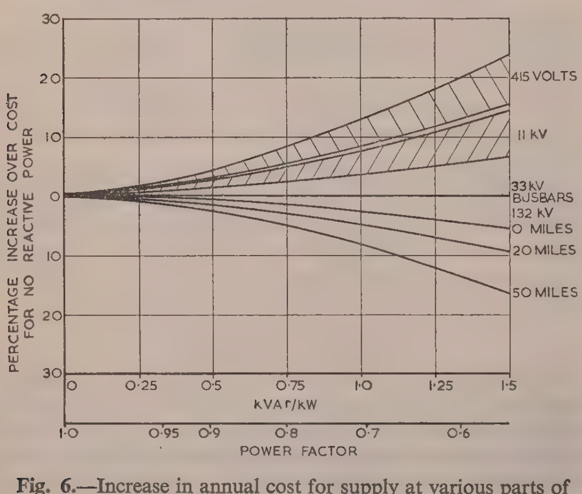


Fig. 6.—Increase in annual cost for supply at various parts of system.

(5.5) Effect of Tapped Loads and Variation of kVAr/kW Ratio and Load Factor

The foregoing consideration of costs has related to loads wholly supplied at the terminal point of the system. It is now proposed to indicate the effects of loads taken at different points and having different kVA/kW ratios.

Referring to Fig. 5, the cost of providing supply at 11 kV from a system of negligible length is D_1 for a kVAr/kW ratio of zero (unity power factor) and D_2 for a ratio of 1·5 (0·55 power factor). The difference between the ordinates, i.e. $(D_2 - D_1)$, represents the increase in cost for supplying 1·5 kVAr/kW. Similarly $(A_2 - A_1)$ represents the increase in cost for supplying the same load at 415 volts from a system having the assumed maximum length of connection at each voltage, i.e. load at point A on Fig. 4(*a*).

Suppose now that 50% of the load is supplied with 1·5 kVAr/kW at 415 volts and the remainder with 0 kVAr/kW at 11 kV, at points A and C in Fig. 4(*a*). The combined load at the 11 kV busbars will require approximately 0·75 kVAr/kW (0·80 power factor) and the cost of supplying it will be 125% of the bulk supply cost (point C_3 in Fig. 5). Likewise the cost of supplying the 415-volt portion of the load from the 11 kV busbars onward will be $(A_2 - C_2)$, or 38%. The total cost of supplying both loads will be

$$125 + (38 \times 0 \cdot 5) = 144\% \text{ of the bulk supply cost per kilowatt}$$

A substantial change in the load factor from that assumed in the estimates would affect the copper losses. Their cost, however, is only a small part of the total cost of affording supplies and the effect on the curves in Figs. 5 and 6 would be negligible.

(5.6) Effect of Losses

The effect of the active and reactive power losses in a transmission and distribution system is to vary the kVAr/kW ratio. The reactive power generated by the shunt capacitances is usually small compared with that absorbed by the series inductances, except at times of light load, thus resulting in a higher kVAr/kW ratio (lower power factor) at the power station than at the load.

In the distribution system shown in Fig. 4(*a*), for example, under full-load conditions the kVAr/kW ratio would increase from 0·48 (0·90 power factor) at the 415-volt load to 0·52 (0·88 power factor) at the 33 kV bulk-supply-point busbars. For a system having 5 miles of 33 kV overhead line instead of the 3 miles of cable, and supplying the same load, the kVAr/kW ratio would rise to 0·60 (0·86 power factor) at the 33 kV busbars. At half these loads the kVAr/kW ratio would still increase on the 33 kV overhead line system, but only from 0·48 at the load to 0·51 (0·90 to 0·89 power factor) at the 33 kV busbars. On the 33 kV cable system the kVAr/kW ratio would actually diminish from 0·48 at the load to 0·39 (0·90 to 0·93 power factor) at the 33 kV busbars.

(6) THE EFFECT OF POWER-FACTOR CLAUSES IN CONSUMER TARIFFS

(6.1) Application of Tariffs

The previous Section has indicated the cost of supplying reactive power in addition to active power for inductive loads, which depends chiefly on the reactive-power demand at the time of maximum load. It is now proposed to consider the various tariffs which afford possible ways of reimbursing the supply authority for the additional cost, or of persuading consumers with inductive loads to provide their own sources of reactive power.

Numerous methods of tariff adjustment have been applied, of which the following are examples:

(a) Combined charges for active and reactive power, i.e. a kVA demand charge.
(b) Separate charges for active and reactive power, i.e. kW and kVAr demand charges.
(c) Demand charge for active power only with adjustment based on 'average power factor'.
(d) Demand charge for active power plus charge based on equipment provided (or deemed to be provided) locally by supply authority to generate reactive power.

The kVA demand charge is the simplest method of combining in a single indication the demands for active and reactive power, although the combination is justifiable only if the two maxima occur simultaneously, which is usually the case. Only one demand indicator is required but the most accurate types of instrument are more expensive than kW demand indicators. The concept of kVA demand may not be easy to explain to many consumers and the quantity is not capable of easy legal definition. The effect of a tariff incorporating a kVA demand charge is indicated in curves (b) of Figs. 7 and 8 for 11 kV and

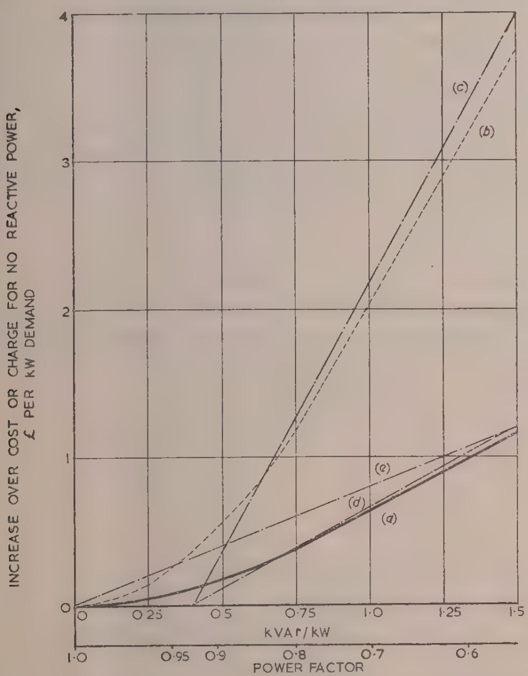


Fig. 7.—Increased cost and tariff charges for supply of reactive power at 11 kV.

(a) Increase in annual cost for system with 3 miles of 33 kV cable and 1 mile of 11 kV cable [Fig. 4(a)].
(b) Increase in tariff demand charge at £4·725 per kVA.
(c) Increase in tariff demand and charge at £3·6 per kVAr for all kVAr exceeding 0·4 kVAr/kW.
(d) Increase in tariff demand charge at £1·1 per kVAr for all kVAr exceeding 0·4 kVAr/kW.
(e) Increase in tariff demand charge at £0·8 per kVAr for all kVAr.

415-volt supplies respectively, while the increase in annual cost of a typical distribution system is shown in curves (a). It is apparent that, if the tariff is correct in recovering costs when there is no reactive-power demand, the supply authority will over-recover their additional costs for reactive power, particularly from the high-voltage consumer. The kVA tariff has proved an excellent means for inducing consumers to limit their reactive-power demands or to provide their own compensation, and has been widely adopted in this country.

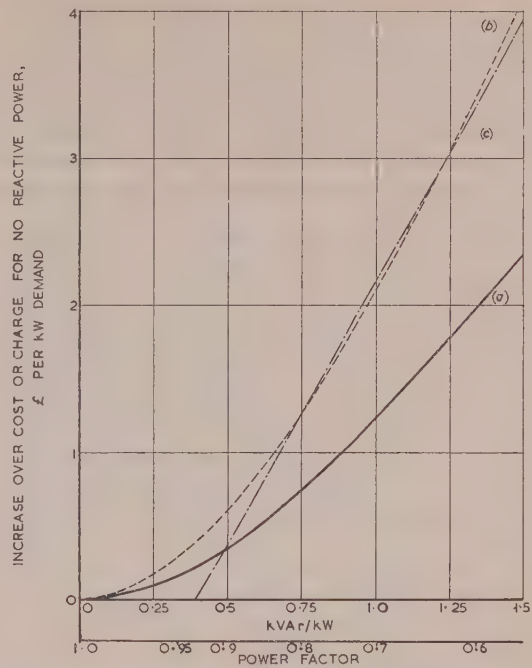


Fig. 8.—Increased cost and tariff charges for supply of reactive power at 415 volts.

(a) Increase in annual cost for system with 3 miles of 33 kV cable, 1 mile of 11 kV cable and 100 yd of 415-volt cable [Fig. 4(a)].
(b) Increase in tariff demand charge at £5·075 per kVA.
(c) Increase in tariff demand charge at £3·6 per kVAr for all kVAr exceeding 0·4 kVAr/kW.

A demand charge having the form £a per kW plus £b per kVAr demand per month or per annum has the advantage of permitting separate indication and adjustment for the two components to meet the cost of each. The effect of a kVAr demand charge which applies to all reactive power is shown in curve (e) of Fig. 7. Comparison with the increased cost of supply [curve (a)] shows that, if correct for no reactive-power demand, it may lead to over-recovery of the additional costs for low values of kVAr/kW. It may thus provide an incentive for the consumer to generate the whole of his reactive power demand at times of peak load, resulting in a net export to the supply system at times of light load. These disadvantages can be overcome by charging only for that part of the kVAr demand which exceeds a certain proportion of the kW demand, e.g. 0·4 as shown in curve (d). The demand charge then becomes £[a kW + b (kVAr − 0·4 kW)]. There is no rebate when the reactive-power demand is less than 40% of the active-power demand. The sole example of a tariff of this type in Britain has the effect indicated in curves (c) of Figs. 7 and 8, and gives a strong inducement for consumers to limit their reactive-power demands to 40% of their active-power demands, but not lower.

A demand charge for active power only, with adjustment based on 'average power factor', normally requires measurement of kW demand, kWh and lagging kVArh, the average power factor being derived from the relationship between the kWh and lagging kVArh. A ratchet device is usually fitted to the kVArh meter. The main advantage lies in the simplicity of the metering, but a drawback is that the average power factor (and kVAr/kW ratio) of a consumer may differ widely from that at the times of his maximum load. The increased costs incurred by the supply authority depend chiefly on the kVAr/kW ratio at the time of maximum system load, and the power factor of the consumer's

maximum demand is likely to be a much closer indication of this than the average power factor over a period of a month. The effect of the tariff depends on the way in which the average power factor is used to adjust the demand charge. Examples are shown in Fig. 9. It is obvious that a demand charge which is proportional to (active power)/(average power factor) will have the same effect as a kVA demand charge if the average power factor coincides with the power factor at the times of maximum load [curve (*a*) in Fig. 9].

A demand charge for active power plus charge based on equipment provided (or deemed to be provided) locally by the supply authority to generate reactive power has not been employed in Britain but is used abroad to a considerable extent. It has the advantage of enabling the supply authority to determine to what extent local sources of reactive power shall be provided and it limits the consumer's responsibility for such equipment to the provision of accommodation. Its equitable application necessitates the assessment (by metering or otherwise) of the consumer's reactive demand, so that the additional charges he is called upon to bear can be related to his requirements and not to the amount of shunt capacitance the supply authority may decide to install, possibly to generate reactive power for other consumers in addition.

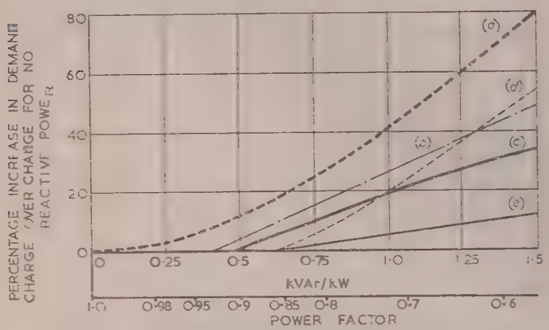


Fig. 9.—Effect of tariff adjustment for power factor on demand charge.

(*a*) kVA demand.
(*b*) kW + 0·45 (kVAr above 0·4 × kW).
(*c*) kW + 1% for each 0·01 below 0·9 power factor.
(*d*) kVA × 0·85 for power factor below 0·85.
(*e*) kW + 2% for each 0·05 below 0·85 power factor.

Since the nationalization of the electricity supply industry, standard industrial maximum-demand tariffs have been introduced by most of the Area Boards as part of the policy of applying uniform tariffs throughout each Board's area of supply. All the industrial and many of the commercial demand tariffs offer some inducement to consumers to limit their demands for reactive power, the methods which were applicable in January, 1961, being shown in Table 2.

It will be noted that seven of the fourteen Electricity Boards in the Table have adopted what is in essence a kVA maximum-demand basis, one employs kVAr demand, three use kW demand divided by average power factor, and three use other adjustments based on average power factor. The effect of the various methods of adjustment is shown in Fig. 9, which indicates that part of the divergence between them is due to the absence in some tariffs of any inducement to reduce the reactive demand below 0·62, 0·50 or 0·40 kVAr/kW.

Table 2

POWER FACTOR ADJUSTMENTS IN CONSUMER TARIFFS 1961

Electricity Board and class of tariff	Basis of maximum-demand charge in tariff to take account of power factor	Power factor below which an additional charge is made	Fig. 9 curve
Industrial and Commercial			
Southern	kVA	1·0	(*a*)
Eastern			
East Midlands			
Midlands			
Yorkshire			
Commercial			
London	kVA × 0·85 if p.f. is below 0·85	0·85	(*d*)
South Eastern			
Industrial and Commercial			
Merseyside and North Wales	kVAr charge (approximately 45% of kW charge) for each kVAr in excess of 0·4 × kW demand	0·93	(*b*)
Industrial and Commercial			
South of Scotland	$\mathrm{kW} \times \dfrac{1}{\text{average p.f.}}$	1·0	(*a*)
Industrial			
North of Scotland	$\mathrm{kW} \times \dfrac{0 \cdot 9}{\text{average p.f.}}$	1·0	(*a*)
Industrial			
South Wales	$\mathrm{kW} \times \dfrac{0 \cdot 85}{\text{average p.f.}}$	1·0	(*a*)
Industrial and Commercial			
South Western	kW plus 1% for each 0·01 below 0·9 average p.f.	0·90	(*c*)
North Western			
Industrial			
North Eastern	kW plus approximately 2% for each 0·05 average power factor below 0·85	0·85	(*e*)

In view of its extensive use, the kVA demand basis is used in this paper as the main standard for comparison with the increased costs of supply and with the costs of reactive power generation by the consumer or the supply authority.

(6.2) Economics of Reactive-Power Generation by Consumer

It is inherently desirable that the reactive power required by any load should be generated as near to the load as possible, thus limiting the current in the connecting circuits to that required to transmit the active power, plus the losses in the circuits themselves. These circuits will, in general, include part of the supply system and part of the consumer's installation.

The provision of a tariff inducement for a consumer to generate reactive power gives him full scope to select the method of doing so which is most advantageous for him, having regard to the distance of his chief reactive loads from his point of supply, the hours of use of his plant and diversity between the demands of individual items. He may, for instance, choose to install a synchronous motor for a drive which is in constant use, or he may prefer to rely entirely on static capacitors. The latter method is used in the paper as a convenient basis for estimating the cost of reactive-power generation.

The case of an 11 kV consumer may be taken as an example. For a given load, say 1 MW, the capital cost of his capacitor installation will include part (related to switchgear, protection and control relays) which is virtually independent of the capacitor rating and part which is approximately proportional to that rating. Details are given in Section 10.3.

In deciding whether to install capacitors and so avoid some or all of the increased tariff charges for reactive power, the consumer will regard them in the same way as other plant and will seek a return which will enable his capital outlay to be amortized within a short period, such as five years. The annual costs for a capacitor installation are shown by the broken lines in Fig. 10, and when these are added to the increased tariff demand charges shown in curve (*a*), the curves (*b*)–(*e*) are obtained for load kVAr/kW ratios (at the time of maximum demand) of 1·25, 1·0, 0·75 and 0·5 respectively.

Curves (*b*)–(*d*) show that significant savings will accrue to the consumer by correcting from 0·75 kVAr/kW or more (0·8 or lower power factor) to the optimum of about 0·2 kVAr/kW (0·98 power factor), but curve (*e*) shows that under the conditions assumed the kVA tariff will provide no incentive for him to install capacitors if the load requires as little as 0·5 kVAr/kW (0·89 power factor).

The effect of a kVAr tariff is to enable comparison to be made directly between the annual savings and the annual costs of capacitors. For example, if the consumer's load of 1 MW has a reactive demand of 1 MVAr (0·71 power factor), the kVAr charge will apply to 600 kVAr. Taking this as £3·6 per kVAr per annum, as in curve (*c*) of Fig. 7, the annual tariff cost will be £2 160, or £2·16 per kW demand. The annual cost of 600 kVAr of shunt capacitors, on the basis assumed for Fig. 10, will be £0·68 per kW demand, so that the installation of capacitors would result in a net annual saving of almost £1·5 per kW for the first five years and over £2 per kW afterwards. The consumer will thus have a strong inducement to generate all his chargeable reactive-power demand and take only 0·4 kVAr/kW from the supply system.

(6.3) Economics of Reactive-Power Generation by Supply Authority

The supply authority can offer the consumer a tariff incentive to generate reactive power, but the consumer has the freedom to decide whether he will invest capital in this manner or pay additional revenue for the whole of his reactive-power requirements. If he elects to bear the increased tariff charges, the choice between local and remote generation of reactive power passes to the supply authority.

The additional cost of distribution for a typical 11 kV supply is indicated by curve (*a*) of Fig. 7, and repeated as curve (*a*) of Fig. 11. In considering the expenditure of capital on static capacitors or other means of local generation of reactive power, the Area Board has the advantage of being able to take a much longer view than is possible for most consumers. The amortization period for plant and machinery is 25 years, in contrast to the 5 years assumed for the consumer.

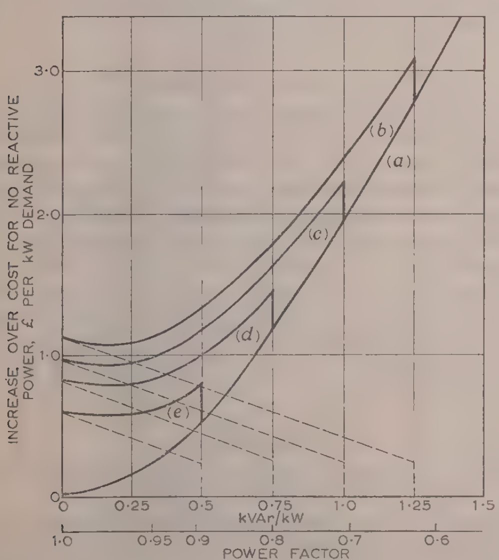


Fig. 10.—Increase in tariff demand charge and cost of full or partial reactive generation by 11 kV consumer.

(*a*) Increase in annual demand charge (£4·725 per kVA).
(*b*)–(*e*) Increase in demand charge plus capacitor costs for load kVAr 1·25, 1·0, 0·75, 0·5 per kW.

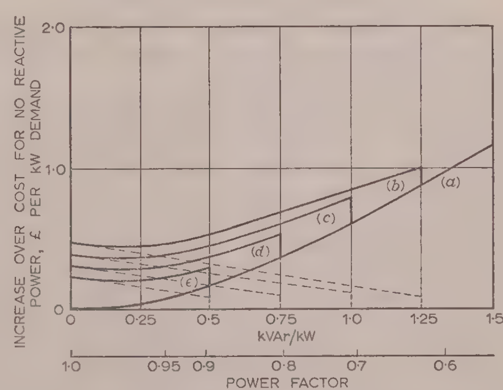


Fig. 11.—Increase in system cost and cost of full or partial reactive generation by Electricity Board.

(*a*) Increase in annual cost of system.
(*b*)–(*e*) Increase in annual cost of system plus capacitors installed by Electricity Board, for load kVAr 1·25, 1·0, 0·75, 0·5 per kW.

If the same capacitor installations as in Fig. 10 are provided by the supply authority, the annual costs will be as shown by the broken lines in Fig. 11. If these costs are added to the increased system costs shown by curve (*a*), the curves (*b*)–(*e*) are obtained for load kVAr/kW ratios (at the time of maximum demand) of 1·25, 1·0, 0·75 and 0·5 respectively. It is evident that the supply authority will secure a significant saving by correcting from 0·75 kVAr/kW or more (0·8 or lower power factor) to the optimum of about 0·2 kVAr/kW (0·98 power factor), but curve (*e*) shows that the provision of capacitors would not be economic if the kVAr/kW ratio were as low as 0·5 (0·89 power factor).

In general, it can be expected that present tariff adjustments will persuade most industrial consumers to reduce their reactive demands to between 0·2 and 0·5 kVAr/kW (0·98–0·89 power factor) and it is evident that an Area Board will then have no further advantage to gain by installing further capacitors on the distribution system.

(7) CONCLUSIONS

(7.1) Control of Reactive Power and Voltage

An automatic or semi-automatic scheme of control is desirable to cope with the increasing magnitude and range of variation of reactive-power requirements, and this will necessitate the preparation of hour-by-hour forecasts for both demands and supplies. The programme of planned reactive outputs from generators will include the tappings to which the generator transformers are to be set and also the settings of their voltage regulators. Automatic voltage-regulator settings will also be specified for synchronous compensators and other variable sources of reactive power.

An optimum lagging kVAr/kW ratio is desirable at bulk supply points if best use is to be made of the generators on load to supply reactive power, and this should be kept constant, if necessary by the local provision of suitable compensating equipment.

(7.2) Technical and Cost Studies

The studies in Section 5 show that there is little technical difficulty in keeping the voltage at the end of typical circuits within acceptable limits of variation.

The cost of 33 kV supply after transmission for 20 miles at 132 kV and transformation to 33 kV is about 2·9% more when the load includes 0·75 kVAr/kW (0·8 power factor) than when it consists wholly of active power. The corresponding increase in the cost of distribution, for the typical system lengths shown in Fig. 4(*a*), is 4·4% at 11 kV and 7·5% at 415 volts. A range of typical costs is summarized in Table 3.

Table 3

PERCENTAGE INCREASE IN COST PER KILOWATT FOR TRANSMITTING AND DISTRIBUTING REACTIVE POWER

System conditions	Increase in cost			
kVAr/kW	—	0·30	0·50	0·75
Power factor	1·0	0·96	0·89	0·80
	%	%	%	%
132 kV transmission and transformation to 33 kV (20 miles average)	—	0·5	1·4	2·9
Transmission plus distribution to 11 kV	—	1·1	3·3	6·7
Transmission plus distribution to 415 volts	—	1·5	4·5	9·4

These figures would represent the average increase in demand charge which should be obtained from consumers who take reactive power from the supply system in order to cover fully the increased costs of its transmission and distribution. In view, however, of the need to avoid reducing the kVAr/kW ratio at the bulk supply points below the optimum, which for the conditions postulated when the total load reaches 30 GW would amount to 0·4 (0·93 power factor), it may be inadvisable to apply tariff adjustments for reactive-power demands which do not exceed 0·3 or 0·4 kVAr/kW.

It should also be noted that the general conclusions based on a typical system are not necessarily applicable to any particular case.

(7.3) Methods of Tariff Adjustment

The most flexible form of tariff is that having separate charges for active and reactive power demands. The price per kVAr in this country should be less than the price per kW and no charge should be made for kVAr less than about 40% of the kW demand. This price difference is likely to be increased as the average cost of all installed generating plant rises, owing to the growing proportion of post-war conventional plant and nuclear plant.

These increases in capital costs will be reflected in increasing demand charges on kVA tariffs, which have the outstanding merit of simplicity. The scale of adjustment for reactive power resulting from kVA tariffs may thus tend to become excessive.

Tariff adjustments based on average power factor appear to be somewhat inequitable for consumers whose kW/time and kVAr/time characteristics differ.

Present methods of tariff adjustment provide a strong inducement to consumers to reduce their reactive demands to between 0·5 and 0·2 kVAr/kW (0·89 to 0·98 power factor) by providing their own sources of reactive power. There is generally no advantage to be gained by installing further sources of reactive power on distribution systems, having regard to the conditions to be expected at times of light load.

(8) ACKNOWLEDGMENTS

Acknowledgment is made to the Central Electricity Generating Board and the Yorkshire Electricity Board for permission to publish the paper. The authors wish to thank various colleagues in the electricity supply industry for their assistance in preparing the paper, including particularly the members of the joint working party of the supply industry which prepared two reports dealing with power-factor correction and the application of series capacitors, and also the members of an *ad hoc* panel which is considering many of the problems of reactive power supply.

The opinions expressed are those of the authors and do not purport to represent the views of the Electricity Boards in England and Wales.

(9) REFERENCES

(1) KAPP, G.: 'Power Factor Improvement', *Journal I.E.E.*, 1923, **61**, p. 89.

(2) BERRY, R. N.: 'Economics of H.V. Transmission by Underground Cables', *ibid.*, 1947, **94**, Part II, p. 573.

(3) CAHEN, F.: 'Increase in the Transmission Capacity of Distribution Systems by the use of Shunt Connected Static Capacitors' (B.E.A. Translation No. 542).

(4) 'Installation and Maintenance of Electrical Machines, Transformers, Rectifiers, Capacitors and Associated

Equipment', British Standard Code of Practice C.P. 321.102, 1950, par. 319.
(5) ERICH, M.: 'Importance of the Reactive Current in the Distribution of Power', *Elektrizitatswirtschaft*, April, 1951 (E.R.A. Translation IB.1137).
(6) STARR, E. C., and HARRINGTON, E. J.: 'Shunt Capacitors in Large Transmission Networks', *Transactions of the American I.E.E.*, 1953, **72**, Part III, p. 1129.
(7) CASH, P. W., and CHORLTON, A.: 'Aspects of Main Transmission-System Development in England and Wales', C.I.G.R.É., Paris, 1958, Paper No. 413.
(8) LALANDER, S., GUSTAVSSON, H., and HOLMIN, N.: 'The Production and Distribution of Reactive Energy', U.N.I.P.E.D.E., 1958, Paper IV–2.
(9) 'System Planning of Reactive Supply', Edison Electric Institute Publication No. 58–9, September, 1958.
(10) MASON, T. H., AYLETT, P. D., and BIRCH, F. H.: 'Turbo-Generator Performance under Exceptional Operating Conditions', *Proceedings I.E.E.*, Paper No. 28465, January, 1959 (**106** A, p. 357).
(11) POWELL, E. B., MUTCH, W., STALEWSKI, A., TOMS, J. E.: 'Synchronous Condenser Operation of Turbo-Generators', C.I.G.R.É., Paris, 1960, Paper No. 104.

(10) APPENDICES

(10.1) Estimates of Cost of Transmitting both Active Power and Reactive Power

The assumptions made for each section of the system shown in Fig. 4 are given in Table 4. The maximum load and permissible limit of voltage regulation are applicable to the normal condition in which all circuits are in use.

The capital costs have been estimated at present-day prices and the annual charges derived by means of the assumptions shown in Table 5.

In estimating the components of the losses which depend on the load (i.e. those in 'series' elements of the circuits) they have been assumed to have an annual load factor $(0\cdot2f+0\cdot8f^2)$, where f is the load factor of the load.[2]

Table 4

DETAILS OF SUPPLY SYSTEM

Voltage	Conductor size or transformer rating	Maximum load	Load factor	Cost of losses		Permissible limit of voltage regulation
				Per kW	Per kWh	
kV		MVA		£	d.	%
132	0·175 in² line	57	0·46	6·0	0·51	5
132/33	45 MVA	28·5	0·46	6·0	0·51	5
33	0·30 in² cable	12·5	0·44	7·1	0·51	} 5
33/11	15 MVA	12·5	0·44	7·1	0·51	
11	0·20 in² cable	3·44	0·40	8·5	0·51	—
11/0·415	0·5 MVA	0·40	0·35	8·5	0·51	—
0·415	0·10 in² cable	0·10	0·30	10·0	0·51	—

Table 5

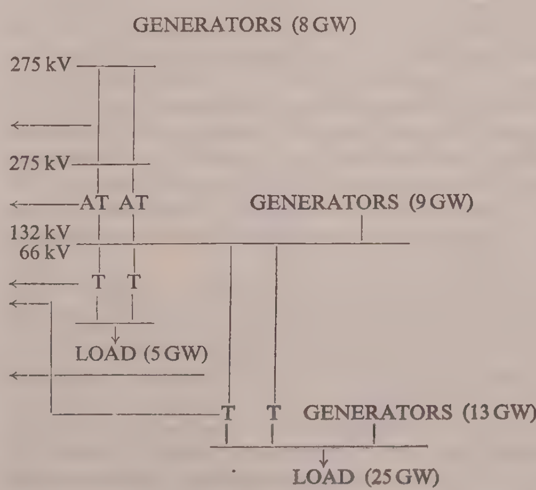
CAPITAL CHARGES FOR SUPPLY SYSTEM

	Assumed life	Interest	Depreciation	Maintenance	Total annual charge
	years	%	%	%	%
Plant	25	5·5	1·95	2·5	9·95
Transmission line	40	5·5	0·73	2·5	8·73
Cable	40	5·5	0·73	1·5	7·73

(10.2) Calculation of Transmission-System Reactive-Power Consumption and Generation

Table 6

	Item	Gain	Loss	
		Shunt	Shunt	Series
		GVAr	GVAr	GVAr
a	30 × 50 miles D.C. overhead line 3 000 circuit miles	1·34	—	0·58
b	178–120 MVA Auto-transformers 21·4 GVAr	—	0·16	0·8
c	936–45 MVA Transformers 42 GVAr	—	0·74	1·05
d	250 × 20 miles D.C. overhead line Cable circuit miles 132 kV—420 66 kV—800	0·82 0·94 0·8	— — —	0·37 — —
		3·9	0·9	2·8
e	Total at 100% load	+3·0		
		+0·2 GVAr		



T = Two-winding transformers.
AT = Auto-transformers.

(10.3) Estimates of Cost of Providing Reactive Power by Means of Shunt Capacitors

It is assumed that the capital costs which do not depend directly on the capacitor rating (switchgear, protection and control relays) are proportional to the active load, and that the capacitor installation for a consumer with a load of 1 MW will cost £$(1\,000 + 2\cdot 5C)$, where C is the capacitor kVAr. Similar capital costs are assumed to be applicable to capacitors installed by the supply authority.

The annual capital charges and losses are estimated on the basis shown in Table 7, and in each case it is assumed that the capacitors are energized for 40% of the time, including the time of maximum demand.

Table 7

CAPITAL CHARGES AND LOSSES FOR SHUNT CAPACITORS

	Capacitors installed by	
	Consumer	*Supply Authority*
Assumed life, years	5	25
Interest, %	6·5	5·5
Depreciation, %	17·56	1·95
Maintenance, %	2·33	2·33
Total annual charges, % ..	26·39	9·78
Losses, watts/kVAr	3	3
Cost of loss m.d., £/kW ..	4·725	8·5
Cost of losses, d./kWh ..	0·671	0·51

DISCUSSION BEFORE THE INSTITUTION, 6TH APRIL, 1961

Mr. J. L. Egginton: In their consideration of distribution and transmission, the authors have assumed the use of series capacitors to reduce voltage drop. However, except for a few experimental installations, they are not used for this purpose. As the costs in the paper involve this assumption, I feel that these figures are not sufficiently reliable to form the basis of a tariff structure. The right place to correct power factor is at the load, and an excellent method is to connect to, say, 80% of the largest motors in the works, shunt capacitors designed to correct 75–85% of the magnetizing current. This method also benefits the consumer's system.

The authors have assumed that synchronous motors are used for base load and run continuously, but this may not be so. In the extreme, they may operate at peak load for only a few hours, the power factor at other times being very low.

Several tariffs are considered in the paper and there are others. An Area Board can only offer a tariff to induce a consumer to correct his power factor. There are, however, many cases where consumers, through ignorance, shortage of money, shortage of space or other reasons, do not take steps to obtain the most economic power factor. In my experience the industrial consumer's p.f. is lower than would be expected from economic comparisons based on the tariff, but since this industrial load is mixed with domestic and commercial load at approximately unity p.f., the overall power factor is probably reasonable.

One tariff has not been mentioned which I prefer to that suggested by the authors. To a very close approximation, generating and transmission costs are proportional to kW maximum demand. On the other hand, distribution costs are approximately proportional to kVA. A tariff which charges, say, £x per kW plus £y per kVA conforms reasonably closely to the cost curve. But even this tariff is unsatisfactory because it is too difficult to explain to the consumer, and despite its disadvantages my preference is for the straightforward kVA maximum-demand tariff. The meters for this cost more, but the total cost of meters on an industrial supply of 100 kW or more is a very small fraction of the revenue.

The kVA maximum-demand tariff is not a difficult one to explain. The consumer can be told that his motor is taking more current than it really needs, and his service connection has to carry the current he is actually taking. But if the voltage is low he takes more current than he should do, and that is unfair to him. So the meter is compensated to charge him for less current when the voltage is low. That is distinctly easier to explain than the tariff which is based upon kW plus a certain proportion of the kVAr minus something else, which must be extremely difficult to explain to the non-technical consumer.

The average-power-factor tariff is illogical. It saves a little on the cost on the meter, but it can lead to unreasonably high power factors at times of light load.

Mr. C. M. Mitchell: The authors have drawn attention to the interesting fact that a transmission line or a cable can be regarded not only as a transmitter of reactive power, but also as a generator of it and a consumer. It is not clear from the list in Section 2 what criterion the authors use to classify their lines. In particular, what is the difference between (*b*) and (*c*), as both seem to refer to circuits along which power flows to a centre of load?

Column 8 of Table 1 suggests that the maximum capacity of generators connected to the distribution-voltage system is 10·6 GVAr, while column 15 shows that the optimum loading is 6·5. If we accept the principle that as much as possible of the reactive-power requirements should be generated as close to the load as possible, and if we assume that the distribution-voltage generators are nearer the load centres than the higher-voltage ones, it would seem that these generators should produce the maximum reactive power of which they are capable, and that the 132 kV machines should supply only any additional reactive power required.

It is interesting to see from Table 1 that the machines are never called upon in this country to run at a leading power factor. This condition may be compared with that in Uganda, where the system has a maximum demand of 120 MW, which is supplied through a network of 820 circuit-miles at 132 kV and a similar length of lower-voltage lines. The reactive power there, which has to be absorbed by the generators at light load, is approximately 50 MVAr, and this figure drops to practically zero on full load. Thus, here at least, the reactive power taken by the consumer is definitely helpful.

To recover the cost of reactive power, I suggest, in view of the paper, that the best solution would be a three-part tariff; i.e. a unit charge to cover the fuel costs of generation, a kilowatt charge to cover the capital cost of generation and a kVA charge to cover the transmission and distribution costs. However, the various curves in Section 6.1 indicate that there is a considerable amount of money involved in not understanding the significance of kVA, and I hope that the tariff adopted will be as simple as possible.

One advantage of separate kW and kVAr metering and charging is that it would be a move towards an easier understanding of the principles underlying the consumption of alternating current. For instance, it could be explained to the small consumer that he is being sold active power and inductive reactive power, that these are separate entities, that he needs both to drive a.c. equipment and that both have to be paid for. Moreover, if the tariff could be worded to suggest a bonus for taking as little reactive power as possible above an optimum figure of, say, 0·25 or 0·4 kVAr/kW, the general principles involved could rapidly become better known.

Mr. F. H. Birch: I would like to supplement the information given on the cost of the various types of reactive compensation

plant by quoting from the findings of a panel set up to study this and related questions. To facilitate comparison, the capital and running costs have been reduced, in Table A, to an annual charge on the assumptions that the plant has a life of 25 years, that money can be borrowed at $5\frac{1}{2}\%$ interest and that the load factor on the compensation plant is 70%.

Table A

Type of plant	Rating	Voltage	Ancillary equipment	Total annual cost
	MVAr	kV		£/KVAr
Shunt capacitor	0·2	0·415	None	0·4
	10	11	Circuit-breaker	0·26
	20	33	Circuit-breaker	0·28
	60	132	Circuit-breaker	0·31
Shunt reactor	7·5	11	Circuit-breaker	0·24
	7·5	33	Circuit-breaker	0·32
	15	132	Circuit-breaker	0·4
	15	132	Isolator	0·29
	60	132	Circuit-breaker	0·22
Synchronous compensator	+20, −10	11	Starting equipment and circuit-breaker	0·82
	+40, −20	11		0·62
	+60, −30	13		0·50
	+100, −50	13		0·44

Shunt reactors provided to compensate long cables may be coupled to the cables through isolators and switched with the cables.

It is important that, on a supply system, there is at all times an adequate reserve capacity of reactive power immediately available. Without such a reserve, a sudden increase in reactive-power demand arising, for example, from the loss of a heavily loaded transmission line depresses the voltage at the load and may give rise to voltage instability and interruption of supply. It should be remembered that the reactive demand on a system may increase instantaneously and call for immediate correction.

Mr. K. C. Parton: From personal experience on system design, the usual criterion deciding the reactive-power requirements is that of adequate capacity for operation under outage and fault conditions. In particular, once the main outage conditions have been covered there is usually plenty of reserve capacity available for control purposes during normal conditions. If this is so in the present system, I wonder whether the elaborate advanced planning of Section 3.2 is really necessary or whether in fact a much simpler basic control scheme could be adopted. For example, one could envisage a simple local control device whereby the summated power factor at a net load or generation point was continuously metered and automatically corrected to a precalculated optimum value. This would avoid any elaborate day-by-day planning and be fully automatic, particularly if shunt transductors were employed. Shunt transductors would have an added advantage for this work as their high speed of response enables them to keep control in situations where voltage instability is a possible danger.

Mr. D. J. Bolton: Figs. 7 and 8 purport to compare the cost of supply of reactive power with the tariff penalties or charges made for it, to a base scaled in kVAr/kW ratio and, alternatively, in power factor. That base, however, does not mean the same thing in the two instances. In the case of the costs it means the power factor of the system, but in the case of the tariff charges it means the power factor of the individual consumer. If all consumers' loads were alike the system load would be merely a magnified version of the individual consumer's load and the kVA tariff would then reflect costs, because it gives a reduced bonus when the power factor approaches unity. As things are, the only way of comparing costs with tariffs is to take some convenient variable like power factor or phase angle and to differentiate the two sets of costs and compare the rates of change.

Similarly, attempts to bring the tariff closer to the costs by extinguishing the power-factor penalty at some point short of unity are equally misguided. The consumer who injects a certain amount of leading reactive power into a lagging system is performing exactly the same service to that system if he improves his own power factor from bad to medium as if he improves it from medium to good.

Taking Figs. 7 and 8 at their face value and comparing the extra costs on the kVA tariff with the extra charges, i.e. comparing curves (*a*) and (*b*), the authors conclude that 'the supply authority will over-recover their additional costs for reactive power'. As curve (*b*) is up to two or three times as big as curve (*a*), this is a considerable under-statement.

The kVAr tariff has two outstanding advantages. First, it gives equal rewards to the consumer for equal services to the system. Secondly, it enables the magnitude of the power-factor charge or penalty to be varied independently of the magnitude of the active-power demand charge. In the kVA tariff those two things are inextricably combined, but not in the right proportions. The Figures indicate a 'preference for separate charges for active and reactive power demands', but unfortunately this preference is not explicitly stated in the paper.

The authors suggest that reactive costs are negligible at an optimum power factor of 0·93, and it would have been helpful if they could have given actual figures for the power factors at the various bulk supply points.

Dr. E. Friedlander: The comparison between the economics of the transductor-capacitor combination and those of a synchronous compensator is difficult, because the combination can have various forms depending upon the ultimate range between maximum inductive and maximum capacitive power. It may be possible to employ a relatively small capacitor and a large transductor in one installation, whereas the situation may be reversed in another. However, as well as the difficulty of defining a fixed cost per kVA, there is also the greater difficulty of assessing correctly all the ancillary advantages or disadvantages. For instance, transductors and capacitors can be easily produced as outdoor equipment, which may not always be convenient with rotating plant, and they do not need heavy foundations.

The losses of the transductor and capacitor are less than those of a synchronous machine, and they vary with the load in a quite different manner. The transductor loss is greatest when the transductor is giving maximum output, and is very low at the point where the capacitor is required to give maximum output, i.e. where the synchronous compensator has its maximum losses.

The enormous speed of response which one can obtain with transductor control is important. Less than 0·1 sec has been obtained on a 1 MVAr unit for the transition from minimum to maximum output. I do not think that any synchronous machine would easily be made to give a comparable performance. With transductor control there may also be appreciable saving in the operation of transformer tap changers.

The authors refer to the application of series capacitors for the limitation of short-circuit power. Technical difficulties may be expected with some radial feeders, because not every type of load is suitable to be applied in series with a capacitor.

If networks are joined by resonating links of reactors and capacitors in series these will, under short-circuit conditions,

automatically turn into soft-reactance couplings, because the capacitor will be short-circuited by its protecting devices. This may be a partial solution to a problem which will increase with the growth of networks.

Mr. S. C. Chu: The authors mentioned that the load conditions given in Table 1 will be reached in two years' time. I should be interested to know the actual annual growth of demand, supply and installed capacity of reactive power under various categories such as, static and synchronous capacitors, consumers' load, transmission lines, transformers, etc., in England and Wales during, say, the past three years. These figures are important for forecasting the reactive load and planning the reactive-power reserves.

With regard to the compensating device, both switched and unswitched static capacitors are being increasingly recognized in America and other countries as indispensable in a power system. An advantage, additional to those mentioned by the authors, is that the application of static capacitors is very versatile and flexible since a small increment can be installed from time to time according to requirements. As each capacitor can be individually fused, it can be replaced easily and quite quickly in the event of a fault. This means that the duration of maintenance or outage for failure, if any, is short. In other words, the reserve reactive-power capacity can be reduced.

Could the authors state the origin of the shunt capacitor/shunt transductor combination? A combination of shunt transductor and transformer might also be a possibility. Have the authors any information on this?

I presume that after the nuclear power-stations in this country are installed, more obsolete steam plants will become available for producing reactive power. It appears that synchronous capacitors will become redundant.

In the third column of Table 2, should not the figure for the North of Scotland be 0·9, and for South Wales 0·85? If 1·0 is to be retained, the column should be headed 'power factor below which an adjustment on charge is made'.

Dr. R. A. Hore: The installation of corrective plant on an existing power system can, initially, effect only a reduction in losses. This saving, being quite small, justifies raising the power factor only to somewhere in the region of 0·85–0·9. As the system load grows, however, it is possible to make greater savings by delaying the heavy capital expenditure of system reinforcement. The maximum benefit is obtained by applying the corrective plant as near as possible to the load. It is frequently economical to correct the power factor to above 0·95 in this way, although the exact figure and the position at which it should be achieved varies with the particular state of system reinforcement at any particular time.

With long-distance transmission, however, it is frequently impossible to reach the thermal limit of plant because of the lower limit of voltage or synchronous stability, and the previous argument for correction does not apply. On the other hand, the voltage and synchronous-stability limits can be raised appreciably by power-factor correction. For example, over 200 miles the load-carrying capacity of three 330 kV lines for a load p.f. of 0·9 can be achieved with two 330 kV lines if the load p.f. is raised to 0·98. Power-factor correction up to unity at peak load could be justified on most transmision schemes. Unfortunately it is impracticable to operate such a system because the receiving-end voltage becomes remarkably sensitive to very small changes in the reactive power taken by the consumer. To achieve worthwhile saving, very accurate and careful control of the system power factor is essential.

Bulk correction by a consumer is troublesome either because it is not automatic and therefore tends to be left on at times of light load or because it is automatic and not co-ordinated with other automatic equipment in the system. Correction by switching capacitors with induction motors is practicable up to a certain limit after which there is a danger of self-excitation of the motor when it is switched off. This method of correction is very suitable for raising the power factor to that figure determined by the optimization of losses.

It is clear that the optimum power factor for particular parts of power systems varies with both the load and the stage of development. It cannot be achieved by a tariff because, to realize the benefits of deferring capital expenditure or raising transmission power limits, the power-factor correction equipment must be under the supply authority's complete control. The distribution authority can achieve correction more cheaply than the consumer. Table A shows that correction at 11 kV can be obtained at about 70% of the cost of correction at 415 V. The tariff should therefore be strictly fair, charging the consumer the cost to the supply authority. Then only in bad cases will it pay the consumer to correct, and the bulk of the correction will be done more cheaply by the authority and be under its control.

Mr. F. Moores: In reply to a previous speaker, I should like to point out that many low-voltage capacitor installations can be carried out at the same cost as, or even at less cost than, a scheme at 11 kV.

Referring to the question of correction on consumers' premises, it has been stated that it is not always possible to connect sufficient capacitance to motors, and a lot have to be connected in bulk and left permanently joined. For more than 20 years the capacitor manufacturers have been providing low-voltage schemes which are automatically controlled so that the reactive power on the system is kept within predetermined limits, and such an arrangement meets the requirements of the authorities regarding light-load conditions.

Fig. 10 relates to an installation on a consumer's premises at 11 kV and is based upon an amortization period of five years; curve (*e*) indicates that there is no incentive to install capacitors if the power factor is already 0·89. In fact, after five years the equipment would have been just about paid for, and after that there would be a clear annual gain. The expected life of the capacitor should be about 20 years. It would be interesting to draw a similar set of curves for an installation at 415 V based on an amortization period of 10 years, the cost of the capacitors being £100 + 3·75*C*, where £100 represents approximately the cost of a relay for auto-control, and *C* the capacitor kVAr (the cost of solenoid-operated contactors being covered by the figure 3·75). It will then be seen that it is quite economical to install capacitors to improve the power factor to values as high as 0·97 or 0·98, even when it is already 0·89.

Mr. R. O. M. Powell: In view of the statistics presented in Table 1, I would like the authors to consider the position in 10–15 years time from the point of view of equipment replacement. By this time most of the generating equipment that it is planned to use for reactive-power generation will have been replaced or will be approaching replacement. Do the authors envisage that this plant will be replaced by similar equipment connected to the system at the 132 kV level or below, or will the policy be the one suggested in the paper: that of continuing to commission larger machines on the higher-voltage systems of 275 and 400 kV? If the latter is the case, then there will be a very large deficit of reactive power.

In meeting such a deficit, shunt capacitors have been shown, in the paper, to possess very tangible economic benefits. The main disadvantage associated with their use is that control of a bank can, at the moment, only be effected by switching sections in steps. The economic benefits are sufficiently large, however,

to stimulate the development of control systems to overcome present disadvantages. The studies of the transductor/capacitor combination are one example of a development that may completely eliminate this problem.

The suggestion that the Generating Board may find it necessary to penalize an Area Board for excessive reactive-power demands is an obvious step, which has two possible advantages. In extreme cases, Area Boards will have an inducement to generate reactive power in locations where the tariff on the final consumer has resulted in a level of reactive-power generation inadequate for the local system needs. With the Area Boards presented with a standard tariff for their reactive-power demands, it is reasonable to expect that this will be reflected in some standardization of industrial tariffs for consumers.

Mr. A. Abbott (*communicated*): While I agree that reactive-power production can be uneconomical for the supply authorities, they must be able to meet excessive demands at short notice without penalizing the consumer.

Many chemical and by-product plants are of a continuous-process nature. Shutdown on the whole or part of the plant could mean unstable thermal, pressure or chemical conditions with possible damage to plant and danger to personnel. Normal practice in many such plants is to install large horsepower direct-on-line-starting squirrel-cage motors for unit plant drives. Sometimes as many as 15–20 500/800 hp motors at 3·3 or 6·6 kV operate on one busbar-section with arrangements for automatically closing the section switch should the busbar voltage drop to a predetermined value or the main in-feed transformer switch open on fault. The effect of the re-accelerating power required to bring all these motors up to normal speed is to draw a large reactive component from the supply network for a brief period.

Do the authors propose that the consumer should be penalized for this? I believe that the demand for reactive power falls into two categories: a steady-state demand caused by low power-factor plant, which the consumer should either attempt to alleviate or pay a charge for, and a sudden demand due to faults on the consumer's system, which the supply authority must be prepared to meet.

Mr. F. E. Brooker and **Dr. J. M. Cowan** (*communicated*): We have been studying for some time, with colleagues in the Merseyside and North Wales Electricity Board, the problem of controlling the voltage of 11 kV and medium-voltage distribution systems. The investigation is still in progress, but it appears to us that certain preliminary conclusions are justified.

It may prove to be uneconomical to design distribution systems to supply reactive in addition to active power, because this makes the problem of volume control so much more difficult than when active power only is distributed. Where automatic voltage control is available by means of on-load tap changers associated with 33/11 kV transformers, this can be made fully effective only where the load consists exclusively of active power. Under such conditions, the voltage drops between the 11 kV terminals of 33/11 kV transformers and the medium-voltage terminals of the 11 kV/m.v. transformers are relatively low, because this part of the distribution system is predominantly reactive and the product of in-phase current and reactive impedance gives a voltage component which is approximately in quadrature with the system voltage. The automatic-voltage-control feature may be utilized to the full, therefore, in compensating for the voltage drop caused by active power alone flowing in the medium-voltage distribution system.

Distribution systems vary widely in both the impedance of 11 kV and m.v. distributors and the loading of the distributors. It is the variation in these factors which complicates the problem of controlling the voltage; if the kVAr/kW ratio of the loads is an additional variable, the satisfactory control of voltage becomes even more difficult and expensive. Our conclusions are that the kVAr/kW ratio of 0·4 mentioned by the authors will not prove to be a good figure to adopt, and the reactive power should not be distributed on 11 kV and m.v. systems.

[The authors' reply to the above discussion will be found on page 524.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 27TH MARCH, 1961

Mr. G. Lyon: Reactive control for transmission has really become a live issue in England and Wales only with the introduction of the 275 kV network. In many oversea systems reactive control is an inherent requirement, and the transmission losses are sufficient to invalidate the merit-order method of generator loading used successfully on the compact systems in Britain.

The method of adjustment of automatic voltage regulators, described in Section 3.2, seems rather odd. It implies not only that governors control load and not speed, but also that voltage regulators should control only reactive power and not voltage. Instead of the manual resetting described I think it would be desirable to have a measure of automatic control of voltage levels suitably compensated for load, with an appropriately sophisticated compounding method. It may also be found advisable to switch out some lightly loaded lines and to lower the general voltage level under minimum-load conditions. The wide use of on-load tap-changing equipment in Britain seems to favour the latter method.

Table 1 is interesting for its indication of the high level of installed capacity expected soon. Are the authors content to operate, at unity power factor, generators connected to the 275 kV system having short-circuit ratios around 0·4? I would like their views on the possibility of automatic control of reactive power to give the optimum reactive loading quoted. The figures given in column 19 approach one ideal, that of minimum reactive compensation, but this is not the only criterion, and much larger installations will probably be needed for flexibility of control.

Would the authors confirm that the costs quoted for synchronous compensators include installation and auxiliaries as they seem low compared with the static-capacitor costs? Also, are they satisfied to assign a life expectancy of 25 years to the capacitors? The paper treats series capacitors on 33 and 11 kV networks as a routine application. I doubt whether we have reached such a stage of confidence especially in the performance and economy of the necessary protective equipment, but if the authors can quote substantial service experience it would be most interesting to know of it.

The curves in Fig. 10 show that a consumer who decides to compensate a low-power-factor load can benefit by raising his power factor to about 0·98, but I doubt the wisdom of encouraging correction to this degree outside the control of the supply authority, because of difficulties with high or leading generator power factors under light-load conditions.

The conclusions of the paper regarding transmission systems must be treated with some reserve if systems of a substantially different character are being considered.

Mr. P. Richardson: It has been customary to make synchronous capacitors of the salient-pole type of construction, but experience has indicated that as the size of such units increases there is some advantage in turbo-type construction having four poles for ratings of 60 MVA and higher. These units are more

reliable, they have a larger inertia constant and a lower reactance than the equivalent salient-pole machines. This is particularly important for voltage stabilization.

It would seem from the paper that there is a tendency to improve the power factor of large generating plant towards unity, and I think that this might be of more assistance in designing machines of limiting output than further changes in short-circuit ratio below 0·4.

I suggest that Fig. 1 is not a typical performance chart for a generator, and I would like to put in a plea for the retention of the normal capability chart which has been used until now, and which is based on the fundamental vector diagram of a synchronous machine. Such a chart illustrates what is happening to power factor and load angle and is superior, in my view, to the chart shown in the paper.

Mr. T. H. Milne: Looking ahead, beyond the conditions outlined in Table 1, a very different conclusion can be drawn. Consider the conditions in 10 years' time when the system peak load will have reached 50 GW. It can be assumed that the active component of this load will be met by the installation of conventional or nuclear power plant connected to the 275 and 400 kV systems. Following the argument presented in the paper, the optimum reactive load of this new plant will be zero. If by this time the optimum 0·93 power factor at the bulk supply points has been achieved, there will be a reactive component of 20 GVAr on the transmission system. To cope with this, there will be a marginal increase in the generation by shunt capacitance on the transmission system, which could raise the figure of 11·2 in column 17 to, say, 13 GVAr. There would thus be a deficit of 7 GVAr requiring compensation, i.e. 10 times as much as that shown to be required in Table 1.

In this period also, it must be assumed that a significant part of the older generating sets, i.e. those connected at distribution voltage, will have been shut down, and it is mainly upon this item that the balance in the Table depends. Thus, if by 1971 the figure of 6·5 in column 15 is diminished to 3·5, provision will have to be made for an additional 3 GVAr of compensation, bringing the total to 10 GVAr. This, of course, represents a very large programme on a much greater scale than that indicated in the paper. It suggests that after the optimum power factor of 0·93 is achieved the time will come when there will again be pressure on Area Boards and consumers to improve the power factor at the bulk supply points, perhaps from 0·93 to 0·96, and it may therefore be questioned whether 0·93 is an adequate first objective. It is significant and fitting that the incentive to consumers as depicted by the curves in Fig. 10, if taken up fully, would provide a power factor of the order of 0·98. This desirable solution has the merit of dealing with the reactive component at source. An alternative, which will no doubt be largely implemented, is to convert time-expired generating plant to the duty of reactive compensation. This would, however, meet only part of the total requirement and would not remove the reactive component from the transmission system.

The trend of future active- and reactive-power generation would seem to require separation of the two functions. In principle, therefore, if active-power equipment costs say £38 per kilowatt to install, it will be necessary to qualify this by adding a reactive-power cost component, which would seem to be £4 × the kVAr/kW ratio, per kilowatt.

Regarding the offer to the consumer of a tariff incentive to generate reactive power, it is stated that should the consumer refuse to do this the Area Board can then, if it chooses, install a bulk reactive compensating unit. Presumably, subsequent offers from consumers to correct their power factor would not be refused. Would the net result of a number of large consumers deciding to do this tend to sterilize the Area Board's compensating plant?

Mr. N. Young: The usual method of starting synchronous capacitors is to switch them on to a reduced voltage obtained from an auto-transformer, but in remote places the apparent power required is sometimes more than the system can stand. The usual solution is to employ a pony motor to drive the machine up to speed. In an interesting variation of this method, which can be described as combined starting, the synchronous capacitor and an induction motor have their windings connected in series and their shafts mechanically coupled. The supply is connected to the terminals of the synchronous capacitor, and the motor windings are star-connected.

When the circuit-breaker is closed the combination draws current from the system determined by the sum of the reactances. The motor is much the smaller machine and so has a relatively high reactance, and the current drawn from the line is low. The voltage across the motor is a large part of the supply voltage and accelerating torque is developed. When the machines are up to slip speed the synchronous capacitor is excited, and the voltage across it rises. The machines begin to accelerate towards synchronism, and while they are asynchronous the motor voltage drops. When the voltage is a minimum, the star-point switch is closed, and the motor is thus isolated from the supply with which the capacitor synchronizes. The transient disturbance is negligible. Fig. A represents an oscillograph record of a combined start.

Fig. B shows the effect of delaying the star-point closure. Here the synchronous capacitor has synchronized with the supply, and its rotor angle is zero. It behaves as a capacitor and together with the motor, forms a resonant circuit. In these circumstances the voltage across the motor windings can rise above the supply voltage, and closing the star point produces a considerable transient disturbance. To obtain the results shown in Fig. A, the control equipment should be arranged to close the field breaker when the rotor angle is large, so that the maximum dip is achieved in the motor voltage, and to close the star-point switch at the instant of minimum motor voltage. The method is particularly useful for redundant generators in use as synchronous capacitors, as these are rarely designed to be started by the reduced-voltage method, and also for the very largest synchronous capacitors, where the mechanical forces on the windings would be great if the reduced-voltage method were used.

[The authors' reply to the above discussion will be found on page 524.]

SHEFFIELD SUB-CENTRE, 29TH MARCH, 1961

Mr. D. N. Roberts: From a consumer's point of view, the electricity supply tariffs encourage us to maintain a power factor of about 0·95 at peak load, which may be improved by means of either a synchronous or a static capacitor. The latter may take the form of large units at the incoming busbars and may then be automatically controlled, or it may take the form of a number of small units connected across motor terminals and switched with the motors. The latter method would seem to be economically advantageous on motors in excess of 15 hp provided that these were in constant use. It also obviates the possibility of having large amounts of leading reactive power on the busbars owing to the failure of the automatic relays to switch it off. Leading power factors are an embarrassment to the supply authorities. It would be interesting to have the authors' thoughts on this.

Mr. G. F. L. Dixon: Table 2 seems to imply that: (*a*) All

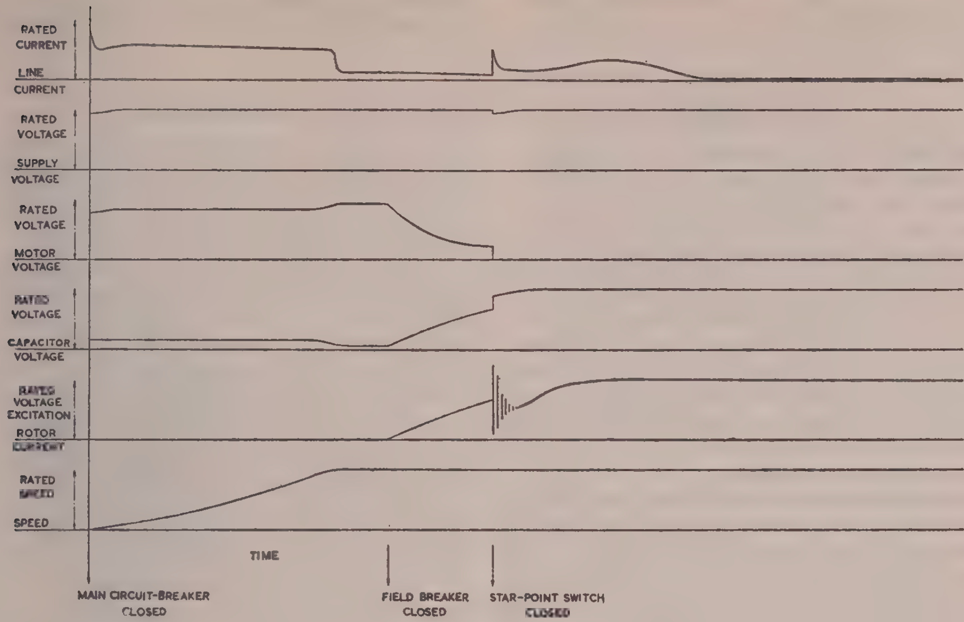


Fig. A

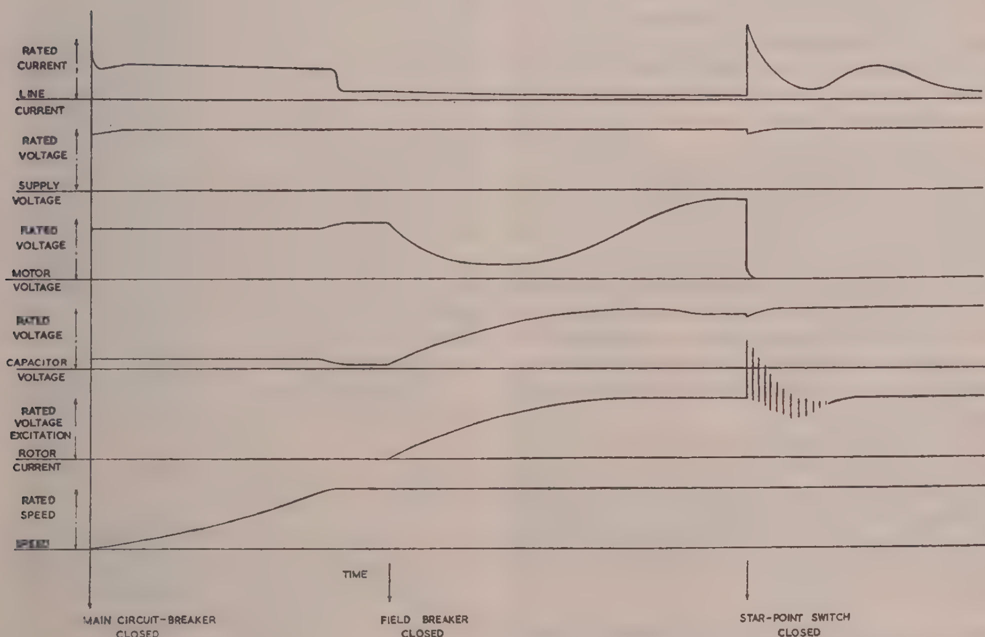


Fig. B

Electricity Boards have recognized that a straight kW demand charge is useless. (*b*) Six Boards are struggling to retain kW demand metering by using clerically modified kW for billing. This seems rather complicated and inflexible, and the various fixed numerical constants may fall inequitably on some consumers. The concept of average power factor is one to view with apprehension. (*c*) Five Boards seem to be satisfied with a straight kVA demand charge. This is better but still has drawbacks. (*d*) Two Boards have attempted to overcome these drawbacks by using clerically modified kVA. This seems rather clumsy, and again we have to use a fixed numerical constant. (*e*) One Board seems to have taken the final logical step, and employs a demand charge composed of separate kW and kVAr components.

As well as its logical structure and flexibility, this last method has the advantages of simplicity of metering and simplicity of

explanation. The consumer is simply told, 'The dial marked "kilowatts" records the unidirectional power flowing from the power station to turn your motors. The other dial, marked "kilovars", records the oscillatory power shuttling uselessly between your motors and the power station. By installing a capacitor you can supply this latter power yourself and avoid paying for it.'

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. W. Casson and **H. J. Sheppard** (*in reply*): We propose to deal with the large number of points raised in the order in which various topics were considered in the paper.

Supply System.—In reply to Mr. Mitchell, the classification of transmission lines in Section 2 results from the operation of the generating plant to achieve the lowest cost of production. The essential difference between (*b*) and (*c*) is that the flow of power in the interconnectors, (*b*), may be in either direction depending on whether a particular centre has a surplus or deficit of generating capacity in relation to its local load at any particular time, while in the bulk feeders, (*c*), the power flow is unidirectional. It will be appreciated that the function of a particular circuit may change when the system is extended or when generating plant is commissioned or withdrawn from service.

There is no doubt that, as stated by Mr. Powell, there will be in the future a need for compensating equipment on a substantial scale to generate reactive power on peak, and to consume it at times of light load. These needs will in large measure arise on the transmission system, but close co-ordination with the Area Boards will be necessary in deciding on the positions in which the bulk compensating equipment shall be installed.

Control of Reactive Power and Voltage.—Mr. Mitchell and Mr. Powell referred to the trend of generating-plant development. The new plant installed in the foreseeable future will consist almost wholly of large generators rated at 200 MW and above and switched directly at either 275 or 400 kV. The withdrawal from service of the older plant switched at 132 kV and lower voltages will undoubtedly result in the need for increased provision for generating reactive power.

We would endorse Mr. Abbott's view that the supply authorities must be able to meet excessive demands for reactive power at short notice; they depend upon the users of such continuous-process plants as those he mentions to provide them with information about the short-time requirements of active and reactive power to bring the motors up to normal speed after the voltage has been depressed under fault conditions. While the supply authorities would not wish to penalize such a consumer, it is equitable that any additional costs incurred in meeting his special requirements should be reimbursed by him and not recovered from the general body of consumers.

We agree with Mr. Richardson that it will be better in future to design generators with higher short-circuit ratios and to operate them at unity power factor. The performance curve shown in Fig. 1 is not claimed to be one which should be used by operating staff, but is considered to be the best form for discussing the performance in the paper, using the concept of conversion of field current into reactive power generated by the exciter.

Mr. Parton does not consider that day-to-day planning of the reactive-power requirements is necessary, but we would emphasize that a high degree of security of operation necessitates at least a daily check on the sources and flows of reactive power. If the base-load generators were provided with an automatic controller to keep the MVAr/MW output constant, and transductors, synchronous compensators or other quick-acting sources of reactive power were employed at points on the system, then we would agree that a close watch on the reactive-power position would not be required.

Mr. Lyon misunderstands our intentions in suggesting the adjustments of the automatic voltage regulator. The idea is to peg the voltage at the bulk-supply points to a fixed value determined by the setting of the automatic voltage regulators of the compensators. The generators are then regulated to obtain a programmed ratio of MVAr/MW, and this means that the generation voltage will vary during the day. With manual adjustment of generator excitation there is no problem, but with an automatic voltage regulator in commission the only way in which this ratio can be maintained is by varying the setting of the regulator. The switching out of lightly loaded lines as a means of reducing high voltage would have an adverse effect on security and is not recommended except possibly in an emergency. We are not aware of any difficulty in operating generators with short-circuit ratios as low as 0·4 at unity power factor, provided that the voltage regulator is always in commission.

It is essential, as confirmed by Mr. Birch, Mr. Parton and Mr. Lyon, to operate with some margin of capacity in hand for supplying additional reactive power to meet such emergency requirements as may arise if a heavily loaded circuit trips on fault. This is the reason for not making full use of the available capacity of generators to supply reactive power, upon which Mr. Mitchell commented, and the relationship between the maximum reactive power available (column 9 of Table 1) and the optimum reactive-power loadings (column 16), a ratio of about 1 to 2, can be regarded as realistic for normal operation.

It is also realistic to provide compensating plant up to the extent of 3·5+ and 2·5− GVAr, even though Table 1 shows a range of only 1·5+ to 0·3+ GVAr. This plant will be located at various points on the transmission system to enable full flexibility to be achieved in controlling both the reactive-power flows and the voltage to cover all conditions of operation.

The information asked for by Mr. Chu, about the consumption of reactive power by various types of load, is very difficult to obtain, and the only information which can be used in practice for transmission planning purposes is the reactive-power demand at various times of the day at bulk-supply points. These figures, which include the consumption in the 66 kV and lower-voltage systems as well as the requirements of consumers, are given for a typical winter weekday in Table B.

Compensating Devices.—We are grateful to Mr. Birch for the information he has given, in Table A, regarding the costs of

Table B

REACTIVE-POWER DEMAND AT BULK SUPPLY POINTS

(National average figures for a typical winter weekday)

Time	Active-power demand	Proportion of peak demand	kVAr/kW ratio	Power factor
h	MW	%		
03.00	7 104	31	0·30	0·96
07.00	11 422	50	0·27	0·97
09.00	19 556	85	0·36	0·94
11.00	19 116	83	0·38	0·93
13.00	17 381	75	0·31	0·96
15.00	17 401	76	0·39	0·93
17.00	19 551	85	0·36	0·94
19.00	18 838	82	0·28	0·97
23.00	14 246	62	0·25	0·97

Based on survey of active- and reactive-power demands, Tuesday, 26th January, 1960. 1959–60 winter peak demand: 23 089 MW, 16.30–17.00 h, Thursday, 14th January 1960.

compensating equipment. This meets the request of Mr. Lyon, and to it might be added the extra cost of a modern generator designed to produce more reactive power at full load. With a 120 MW set designed to operate at a power factor of 0·75 instead of 0·85, the additional capital charges and losses (assuming 70% load factor) would probably give rise to an annual cost of about £0·15/kVAr. Such a machine would be capable of producing an extra 31 MVAr at this cost. We appreciate the advantages of the transductor/shunt-capacitor combination as compared with the synchronous compensator, which were discussed by Dr. Friedlander, and await with interest experience of the operation of such equipment on the transmission system.

In reply to Mr. Lyon, we confirm that the costs quoted for synchronous compensators include installation and auxiliaries. We consider that sufficient experience has now been obtained with static capacitors to justify the expectation of a life of 25 years for them. We thank Mr. Young for supplementing the information we have given by his description of a method of starting synchronous compensators.

The use of generators at obsolete steam stations to supply reactive power has been investigated. The machines are not always situated in the most effective positions for this purpose and the cost of reinstalling them at more appropriate points would be greater than that of providing new compensators. The use of old generators is, therefore, less attractive than is implied by Mr. Chu and Mr. Milne.

Technical and Cost Studies.—Mr. Egginton queries the costs estimated for systems including series capacitors. Where the use of these capacitors is assumed, their cost is only a small part of the cost of the circuit. In Fig. 5, the omission of the series capacitors would affect the percentages shown for 11 kV and 415 V by less than 1% and those for 50 miles at 132 kV by less than 2%. The figures for 0 and 20 miles at 132 kV would be unchanged. We consider that this method of making a small adjustment in the cost estimates is both more convenient and less arbitrary than assumptions about the cost of an increased range of tappings on transformers. Dr. Friedlander and Mr. Lyon also appear to misunderstand our mention and use of series capacitors.

The suggestion of Mr. Brooker and Dr. Cowan, that distribution systems might be designed to supply active power only, appears to be a counsel of perfection. It is fortunate that much of the load supplied by rural 11 kV distribution systems, in which voltage drop is the limiting factor, has a kVAr/kW ratio much lower than the figure of 0·4 which we have suggested as the optimum for loads of an industrial type. There appears to be little difficulty in distributing up to about 0·5 kVAr/kW on most 11 kV and m.v. cable systems, provided that automatic voltage control is effected at the points of supply to the 11 kV networks.

Tariffs.—We thank Mr. Egginton for his support of our view that the right place to generate the reactive power required by any load is as near to the load as possible. It is, of course, necessary to ensure that the compensating equipment is not left in commission when there is no load. We appreciate his point that the installation of synchronous motors will not necessarily ensure that they are being run to generate reactive power at all times when this is desirable, but we suggest that a consumer would not be well advised to install a synchronous motor for a drive which was only in use for a small portion of the operating time of his plant as a whole.

We limited our consideration of tariff adjustments broadly to those which are at present in use in Britain. Mr. Egginton's suggested tariff incorporating both a kW and a kVA demand charge would be flexible in its application, but the metering equipment would be more complicated than that required for the kW plus kVAr tariff which we prefer. We consider that the increasing proportion of the total cost of supply which is represented by the kW charge in the bulk-supply tariff is making a kVA demand charge less equitable between consumers with low and high kVAr/kW ratios, and our preference for the kW plus kVAr tariff remains as stated in Section 7.3, to which we would refer Mr. Bolton. Mr. Mitchell and Mr. Dixon have indicated that the explanation of this tariff to consumers need not be difficult.

In reply to Mr. Chu, the figures in Table 2 are correct. We should make it clear that, in referring to the power factor below which an additional charge is made, the comparison is with the demand charge at unity p.f., which, for the two Boards mentioned by Mr. Chu, is less than the nominal charge per kilowatt stated in the tariff. The effect of the tariffs to which he refers is correctly illustrated by curve (*a*) in Fig. 9.

We agree with Mr. Bolton that there is some measure of approximation in comparing the costs of supply of reactive power with the tariff charges which are applicable to an individual consumer in Figs. 7 and 8, but we suggest that the approximation is no greater than the effect of averaging costs, which is inherent in any system of tariffs. We would also agree that any consumer who injects a given amount of leading reactive power into the system is performing exactly the same service to the system so long as the power factor remains lagging at times of light load as well as heavy load, but to ensure that the system does not go over to leading power factor, a limit must in practice be fixed beyond which the consumer has no encouragement to install further sources of reactive power. It is this consideration of system conditions at times of light load which makes it advisable to ensure that the method of tariff adjustment does not provide consumers with an incentive to reduce their reactive power demands to much less than 0·4 kVAr/kW.

We would support the view of Mr. Moores rather than that of Dr. Hore regarding the provision of capacitor installations on consumers' premises, and thank him for drawing attention to the schemes for automatic control of the larger bulk-correction installations.

We agree with Mr. Moores that a consumer's capacitor installation can be expected to have a life much longer than five years, but such an installation will not compete successfully with other calls upon the capital resources of most consumers unless the outlay can be amortized within a period as short as five years. We would draw attention to the effect of a tariff having an appropriate kVAr demand-charge component. This can be expected to induce the majority of consumers to limit their reactive-power demand to approximately the value at which the charge ceases to apply, which we have suggested should be about 0·4 kVAr/kW.

Mr. Milne suggests that the optimum power factor at bulk-supply points will, within a few years, be higher than 0·93. While this may well be true at times of peak load, the capacity required for absorbing reactive power at times of light load will be much greater also, and we do not consider it would be prudent to offer tariff inducements to consumers to reduce their reactive-power demands below 0·3 or 0·4 kVAr/kW at times of peak load.

We do not share Mr. Milne's view that the installation of bulk reactive-power compensation by Area Boards might be sterilized by the subsequent action of consumers in installing their own plant. It has been found in practice that tariff inducements have been effective in persuading consumers to install their own sources of reactive power, leaving little for the Area Boards to provide.

Conclusions.—Mr. Lyon rightly comments that the conclusions of the paper must be treated with some reserve if systems of a substantially different character are being considered, and we would emphasize that our conclusions relate only to the transmission system of England and Wales.

The Calculation of the Magnetic Field of Rotating Machines

Part 2: The Field of Turbo-Generator End-Windings

By D. S. Ashworth, B.A., and P. Hammond, M.A., Member.

The Magnetic Field of the End-Windings of Turbo-Generators

By P. J. Lawrenson, M.Sc., Graduate.

PREFACE

A knowledge of the magnetic field in the end regions of turbo-generators is essential for the determination of stray losses, leakage inductances and short-circuit forces. The following two papers describe an investigation of this field. Because of the complicated geometry of the windings and boundaries in the end region, it is impossible to determine the field exactly. Nevertheless, it is hoped that the results presented here will be a useful guide to the thoughts of designers.

Although the authors are known to one another, the two papers were written independently. In this way it is possible to give a more comprehensive treatment of the subject and to compare the methods of calculation used in the two papers. Both of these methods, which are of general application, require the use of a digital computer but are otherwise completely different.

The first paper forms the second part of an investigation of the magnetic field of rotating machines. Part 1 ['The Field of a Tubular Current', Monograph No. 333, May, 1959 (**106 C**, p. 158)] gave an outline of a method of calculating the 3-dimensional magnetic field of windings possessing cylindrical symmetry. The method was illustrated by considering the field of a tubular current similar to the rotor current system of a squirrel-cage induction motor.

In Part 2, presented here, the actual windings are represented by single-layer cylindrical current sheets. The method is analytical and formulae are derived for the magnetic field of cylindrical current elements. These enable the designer to see the general effect of varying the machine parameters.

In the second paper the individual coils of the winding are represented by their central filaments. The method yields no analytical results but is extremely simple and is rather more accurate than the first method. It uses the actual coil currents and accounts inherently both for the two layers of the winding and for the pitch of the coils. It also leads inherently to the harmonics and phases of all components of the field.

Using the two methods of calculation for the same problem, the results for the fundamental components of field agree very closely except in the vicinity of the winding (where the effect of the different representations of the winding is significant). However, the results presented in the two papers, though for the same machine, apply to different boundary conditions; in the first paper boundary effects are ignored, whilst in the second the influence of the core end-plate, as dependent upon permeability and the air-gap, is treated.

It is clear that much further work, both theoretical and experimental, is required before the problems discussed in these papers can be regarded as solved. It is hoped that the papers have, however, brought such a solution nearer.

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THE CALCULATION OF THE MAGNETIC FIELD OF ROTATING MACHINES

Part 2.—The Field of Turbo-Generator End-Windings

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SUMMARY

The magnetic field of turbo-generator end-windings is analysed. Particular attention is given to the field at the surface of the stator-core end-plate. The effects of varying the cone angle of the end-winding, the chording angle and the length of the axial portion of the end-winding are discussed. The effect of power factor is considered with particular reference to the large fields observed at leading power factors. Experimental results on a model winding show reasonable agreement with the computed results.

LIST OF SYMBOLS

A_r, A_θ, A_z = Vector potential.
$b = \pi/g$.
g = Spacing between successive current tubes.
H_r, H_θ, H_z = Magnetic field strength.
i_r, i_θ, i_z = Current line density.
$\hat{i}_s$ = Twice the maximum value of current line density in a single stator-winding layer.
I_p, I'_p = Modified Bessel function and derivative of modified Bessel function of the first kind and order p.
K_p, K'_p = Modified Bessel function and derivative of modified Bessel function of the second kind and order p.
$2l$ = Axial length of tubular current elements.
L = Length along generator of cone of stator end-winding.
L_R = Axial length of rotor end-winding.
n, N = Integers.
p = Number of pole pairs.
r = Radius.
R = Radius of current tube or disc.
ΔR = Annular width of current disc.
s = Odd integer.
t = Time.
x = Variable ($0 \leqslant x \leqslant 1$).
Z = Distance from start of conical end-winding to end-plate.
β = Semi-angle of end-winding cone.
2δ = Angular spread of rotor slot conductors.
$\lambda = \dfrac{\pi}{2p} - \mu$.
2μ = Chording angle.
μ_0 = Primary magnetic constant.
ρ, ρ_R = Radius of stator, rotor, current sheet.
ω = Angular frequency.

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(1) INTRODUCTION

The paper forms the second part of an investigation of the magnetic field of rotating machines. In the first part of the work[1] an outline was given of a method of calculating the 3-dimensional magnetic field of windings possessing cylindrical symmetry. The method was illustrated by considering the field of a tubular current similar to the rotor current system of a squirrel-cage induction motor. It is now proposed to apply the method to the end-windings of turbo-generators.

In the past the end-winding field has often been treated briefly under the heading of end-leakage reactance. Frequently such treatment has made it appear that this leakage field is in some sense an imperfection in the design of a machine and that it is of no great importance. Such an impression is misleading.

The leakage field of the end-windings is of great importance. It is directly useful in limiting short-circuit currents and forces. It is also harmful in causing eddy-current losses in the windings and adjacent metal structures such as the core end-plates. Such losses have never been adequately analysed. They are generally grouped together as 'stray' losses and designers have to rely on past experience in estimating these stray losses of a machine. It is therefore highly desirable to analyse the magnetic field of the end-windings as a step towards calculating and reducing the stray losses.

The necessity for such analysis has been underlined by the remarkable increase in the rating of turbo-generators in the last ten years. This increase in rating has been achieved with only a slight increase in rotor dimensions, since these are limited by mechanical considerations. Thus the current loading of the machines has had to be increased sharply and the stray losses have become a major difficulty. The present paper is offered to design engineers as a tool for the calculation of end-leakage fields. It is hoped that the method will enable a correct diagnosis of stray losses to be arrived at. The diagnosis should make possible a less empirical approach to the urgent problem of reducing these losses.

(2) GENERAL CONSIDERATIONS

The method of attack is very similar to that of the previous paper.[1] The actual conductors of the stator and rotor windings are replaced by equivalent current sheets. As before, we ignore in general the effect of iron in the vicinity of the windings. Some allowance for the effect of the stator core can be made by the theory of images.[2] It is hoped to deal with the effect of iron in a future paper and the present work is incomplete. It should, however, be pointed out that this work is an essential stage on the way to a full understanding of the stray losses, because we cannot proceed until we are able to calculate the magnetizing field at the surface of the stator core. Recent papers[3, 4] have sought to deal with the end-field of the windings and the core in one step, but the results are very difficult to interpret. We

propose, therefore, to proceed more cautiously by considering first the field of the windings in air.

We shall deal first with the stator winding, then with the rotor winding and finally with the field due to both stator and rotor windings acting together.

(3) STATOR END-WINDINGS

(3.1) Description of Winding

The stator windings of modern turbo-generators are made up from a large number of identical coils. These coils fit into axial slots in an iron core and there are as many coils as there are slots. Thus there are two conductors, or coil sides, in each slot and the winding is described as a 2-layer winding. The straight slot portion of the coils is known as the active length, and it is here that the electromotive force is induced. The winding is arranged in pole groups and there are generally two such groups in a turbo-generator winding. The end-windings convey the current from each slot to another, which is approximately one pole pitch away. It is usually desirable to make the coil pitch slightly shorter than a pole pitch. This is called 'short-pitching' or 'short-chording' the coil, and reference is made to the chording angle, which will be somewhat less than a pole pitch.

The end-windings are shaped to lie on the surface of a truncated cone. A complete winding is shown in Fig. 1. The

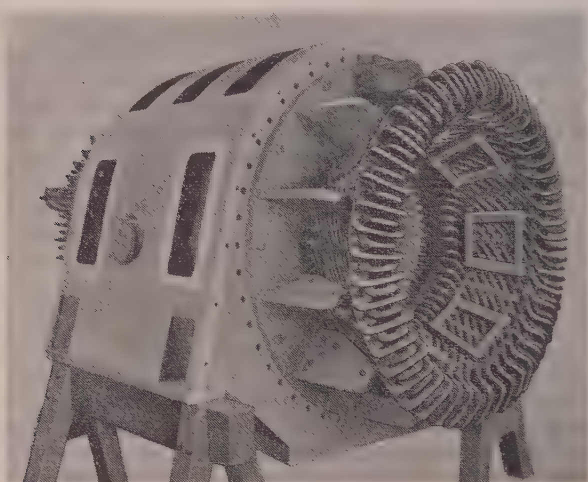


Fig. 1.—Stator end-winding.

track of each conductor on the surface of the cone must be such that it is at a constant distance from the track of an adjacent conductor. This is achieved by following an involute of a circle along the cone surface. Fig. 2 shows two views of a typical coil end; (*a*) is an axial view and (*b*) a developed view on the surface of the cone.

(3.2) Simplified Representation of the Winding

The complicated geometry of the individual coils makes it well-nigh impossible to describe them analytically. We therefore represent the complete winding by a simplified equivalent current distribution. Fig. 3(*a*) shows such a simplified arrangement. The current is supposed to be distributed along thin 'current sheets', which lie along the centre-lines of the actual conductors. We thus have a cylindrical current sheet representing the slot portion and a conical current sheet representing the end-winding. The radius, ρ, of the cylinder, the length, L,

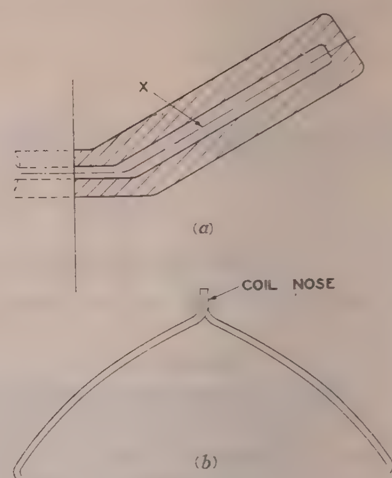


Fig. 2.—Typical involute coil-end.
(*a*) Axial section. (*b*) Development on cone X.

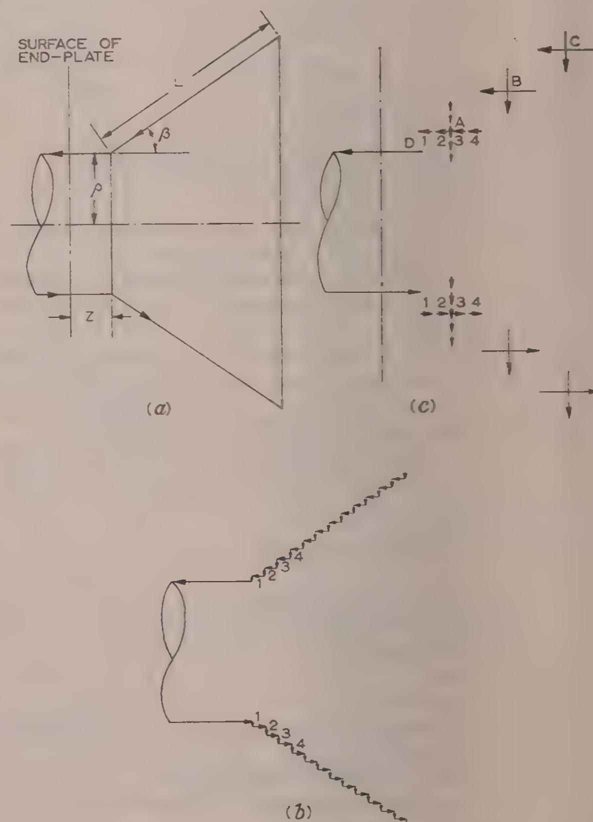


Fig. 3.—Simplified representation of end-winding.

of the cone and the cone semi-angle, β, can be found from the dimensions of the actual machine.

The equivalent current on the surface of the current sheets must everywhere be the sum of the actual currents in the two layers of the winding. The equivalent current will vary with the magnitude of the actual current and with the chording

angle, 2μ. The length, L, of the cone will be related to ρ and β. L has been assumed proportional to ρ, and variation in ρ can thus be treated as a mere scale effect. The independent variables are the cone angle, 2β, and the chording angle, 2μ. The dependence of the magnetic field on these two variables is discussed in Section 5.

The stator end-winding is thus represented by current sheets in the shape of a cylinder and a cone. Since the use of conical co-ordinates is difficult we make the further simplification of replacing the 'conical' current sheet by a series of steps as shown in Fig. 3(*b*). On the conical current sheet the current will flow both along the generators of the cone and perpendicularly to them. In the equivalent representation of Fig. 3(*b*) we suppose that the current flows axially and circumferentially on the cylindrical sheets and that it flows radially on the annular discs.

The conical current sheet of Fig. 3(*a*) can thus be replaced by a stepped current sheet as in Fig. 3(*b*). The steps can be combined into a number of tubes and discs as shown in Fig. 3(*c*). It will be seen that the steps numbered 1, 2, 3 and 4 in Fig. 3(*b*) have been combined into a single disc and a single tube in Fig. 3(*c*). This involves the expansion of steps 1 and 2 and the contraction of steps 3 and 4. The errors introduced by these changes will tend to cancel out.

In Fig. 3(*c*) a final representation of three tubes and discs was chosen to account for the conical end-winding. Clearly it would be possible to improve the accuracy of the representation by increasing the number of tubes and discs. The results of this paper were obtained by using three tubes and three discs. In one case, however, this result was compared with that obtained by using six tubes and six discs. The maximum difference in the field calculated was only 2%. This amply justifies the use of the simpler representation by three tubes and discs.

The magnitude of the current varies along the cone. This variation depends on the cone dimensions and on the chording angle of the winding. A method of calculating the current at any point on the cone is given in Section 11.1. The currents in the equivalent tubes and discs of Fig. 3(*c*) are taken as the components of current on the cone at the mid-points of the tubes and discs.

It should be noted that the current sheets represent the current in all three phases of the actual stator winding. By means of Fourier series it can be shown that the equivalent current can be expressed as a series of rotating harmonics of which the fundamental is strongly dominant. This equivalent current can be described by the expression $i = \hat{\imath} \cos(\omega t - p\alpha)$, where i is the line density of current and α is the angle measured around the stator.

The three components of current flow are represented in Fig. 4. In order to show the angular variation around the stator a 6-pole arrangement is shown. Turbo-generators have, of course, two poles in general, but the treatment is applicable to any number of poles.

(4) METHOD OF CALCULATING MAGNETIC FIELD

(4.1) Use of the Vector Potential

We approach the calculation of the magnetic field by first finding the vector potential A of the current distribution. The vector potential of a current-element is given by the relationship $\delta A = \mu_0 I \delta l / r$, and it will be seen that the vector potential is parallel to the current from which it is derived. If the current has a simple geometry, so has the vector potential; for instance, an axial current gives rise to an axial vector potential. It is thus relatively easy to integrate δA and the magnetic field can then be obtained from the relationship curl $A = \mu_0 H$.

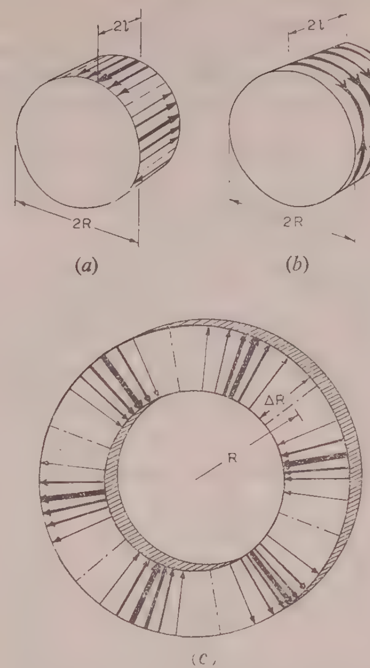


Fig. 4.—Cylindrical current sheets.

(*a*) Axial current sheet. (*b*) Circumferential current sheet.
(*c*) Radial current sheet.

An alternative approach would be to use the Biot–Savart law $\delta \boldsymbol{H} = I \delta \boldsymbol{l} \times \boldsymbol{r} / 4\pi r^3$ without mentioning the vector potential. However, the resulting integration is likely to be very troublesome, because the magnetic field is at right angles to the current-element and to the radius vector drawn from the current-element to the field point.

There is another advantage in the use of the vector potential in that the method can be applied to high-frequency problems by using a delayed current. The Biot–Savart law, on the other hand, while quite satisfactory at power frequencies, is inapplicable to the calculation of magnetic fields at high frequencies. Thus the method adopted by us is of very general application and does not apply only to the problem of turbo-generators discussed in this paper.

(4.2) Method of Computation

The method is set out in detail in Part 1 of the work.[1] Cylindrical co-ordinates are used and the three components of the magnetic field are expressed as infinite series of products of modified Bessel functions and circular functions. The relevant expressions are derived in Section 11.2. In Part 1 the computations were carried out by hand, but the present work was done by means of an electronic digital computer.

Examination of the expressions for the magnetic field reveals that the variation of field with θ is sinusoidal in the same way as the postulated current distribution. This must be so because the system is linear. Thus harmonics in the magnetic field must be due to harmonics in the current distribution. If harmonic fields are likely to be of interest, they can be obtained by the superposition of a harmonic current on the fundamental component of current.

The expressions for the magnetic field also show that the magnitude of the field is unchanged by altering the scale of the linear dimensions as long as the current line density (ampere

conductors per metre) is unchanged. For a 2-layer winding we can describe the line density in a single layer by an expression $i = \frac{1}{2}\hat{\imath}_s \cos(\omega t - p\alpha)$. The value of $\hat{\imath}_s$ will be determined by the actual conductor current and will be independent of chording angle. The results given in Figs. 5–10 are calculated for $\hat{\imath}_s = 1$

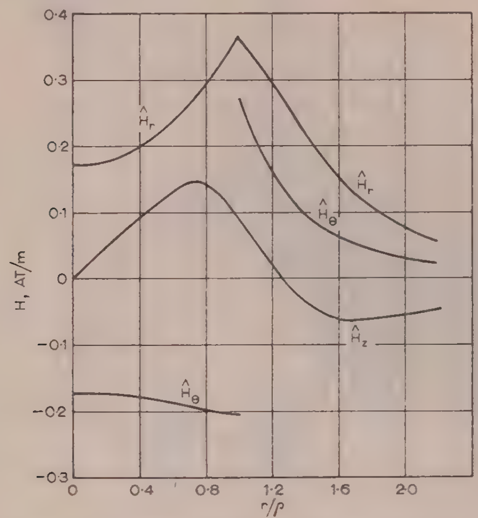


Fig. 5.—Magnetic field of end-winding only.

and are plotted against a dimensionless co-ordinate (i.e. the ratio of two radii). These curves are thus applicable to machines of any size. To obtain the magnetic field for any particular machine it is merely necessary that the field obtained from the curves be multiplied by the actual value of $\hat{\imath}_s$.

(5) COMPUTED RESULTS FOR STATOR WINDING

In Part 1 of the work the field of a simplified winding was examined for both a 2-pole and a 4-pole machine. It was shown that the magnetic field of a 2-pole machine of a certain current loading is always greater than the field of a similar machine with more poles. This result can be seen intuitively since the fields of alternate poles will tend to cancel out at a distance. Mathematically the result follows from the behaviour of the Bessel functions. The order of the functions is related to the number of poles. The fact that a 2-pole field is stronger than a multi-pole one is in fact well known in practice. Stray losses are far more troublesome in steam-turbine-driven generators than in water-turbine-driven generators, which run more slowly and have a larger number of poles.

Our computations have been confined to the case of 2-pole machines and only the fundamental of field considered. It was found to be convenient to use a machine rated at 6·5 MW. The method is, of course, competent to deal with any number of poles and with machines of any rating and dimensions.

(5.1) Magnetic Field at Surface of Core End-Plate due to Stator End-Winding in Air

The stator end-winding is represented by tubes and discs as shown in Fig. 3(*c*). The tubes and discs at A, B and C represent the conical portion of the end-winding. The tube at D represents the cylindrical portion. By use of the formulae of Section 11.2 the components of the field due to each tube and disc are found at any radius. The total field is then obtained by superposition.

The values to be substituted in the formulae are the line current densities ($\hat{\imath}_r$, $\hat{\imath}_\theta$, $\hat{\imath}_z$), the radii of the tubes, which are also the mean radii of the discs, R, the annular widths of the discs, ΔR, the lengths of the tubes, $2l$, and the distances, z, of the core end-plate from the mid-points of the tubes. The computer programme was arranged to accept these values and to sum the fields of the individual tubes and discs, thus giving the field of the complete winding.

All these values can be calculated from the machine parameters by use of Section 11.1. The parameters required, and their values for the particular machine chosen, are shown in Table 1.

Table 1

PARAMETERS OF STATOR WINDING OF 6·5 MW GENERATOR

$$2\mu = 150^\circ$$
$$L = 0{\cdot}302\,\mathrm{m}$$
$$\rho = 0{\cdot}442\,\mathrm{m}$$
$$\beta = 30^\circ$$
$$Z = 0{\cdot}11\,\mathrm{m}$$

[see Fig. 3(*a*)].

For this machine the number of pole pairs, p, is 1. As already explained in Section 4.2, $\hat{\imath}_s$ was taken as unity. The constant, g, which determines the convergence of the infinite series (see Section 3.4 of Part 1) was taken as $g = 5\,\mathrm{m}$. These parameters result in Table 2.

Table 2

EQUIVALENT CURRENT SHEETS FOR STATOR END-WINDING OF 6·5 MW GENERATOR

Tube or disc	$\hat{\imath}_z = -\hat{\imath}_r$	$\hat{\imath}_\theta$	R	ΔR	l	z
	A/m	A/m	m	m	m	m
A	0·840	1·02	0·467	0·0504	0·0437	0·157
B	0·520	1·75	0·518	0·0504	0·0437	0·241
C	0·168	2·16	0·568	0·0504	0·0437	0·329
D	0·966	0	0·442	0	0·0550	0·055

The resulting magnetic fields are plotted in Fig. 5. The step in H_θ at $r/\rho = 1$ must be proportional to the axial current at that place and affords a useful check. Another check is that H_r and H_θ must be numerically equal on the axis of the tubular current sheets.

For the 6·5 MW machine considered here the air-gap is at $r/\rho = \frac{3}{4}$ and the stator end-shield at $r/\rho = 2{\cdot}1$. The full-load conductor current is 806 amp (r.m.s.). There are 36 slots and 4 conductors per slot. Thus the current line density per layer is $\hat{\imath}_s = 5{\cdot}7 \times 10^4\,\mathrm{A/m}$. The values of H_r, H_θ and H_z in Fig. 5 must therefore be multiplied by $5{\cdot}7 \times 10^4$ to give the end-winding field at full-load current. The multiplying constant of a modern hydrogen-cooled machine might well be about three times this figure.

(5.2) Magnetic Field due to Stator End-Winding and Slot Portion in Air

The stator winding can be divided into a slot-portion with an end-winding at each end. It is reasonable to ignore the distant end-winding when we are computing the field on a plane corresponding to the surface of the core end-plate. We must, however, consider the contribution of the slot portion. This section of the winding can be represented by a tubular current sheet carrying axial current. In our example of a 6·5 MW generator the values for computing the field of a slot portion of axial length, $2l$, of one metre are as shown in Table 3.

Table 3

EQUIVALENT CURRENT SHEET FOR STATOR SLOT PORTION OF 6·5 MW GENERATOR

$i_z = -i_r$	i_θ	R	ΔR	l	z
A/m	A/m	m	m	m	m
0·966	0	0·442	0	0·5	−0·5

The distance z is negative because the slot portion lies on the other side of the plane of the core end-plate. It was found that the magnitude of the field was very insensitive to a change of axial length of the slot portion, as long as this length was considerable. In particular a length of 2 m gave the same field as a length of 1 m. This shows that it must be substantially correct to neglect the distant end-winding.

The total field at the end-plate due to the complete stator winding in air can thus be found by adding the field of a 1 m-long tube to the field of a single end-winding. This total field has been plotted in Fig. 6. It is of interest to note that H_z is the same as in Fig. 5, since the axial current of the slot-portion cannot give rise to axial field.

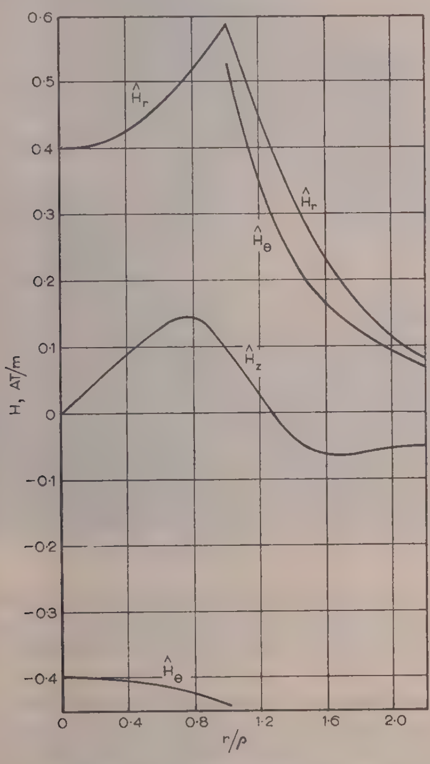


Fig. 6.—Magnetic field of end-winding and slot portion.

(5.3) Variation of Magnetic Field with Cone Angle of Stator End-Winding

The variation of field for a range of cone semi-angle, β, from 10° to 90° is shown in Figs. 7–9. The machine parameters, including cone length, L, and the length, Z, remain constant. The length of the straight portion of conductor was taken as 1 m within the core. It should be noted that the curves for a cone semi-angle of 90° have been obtained by extrapolation. The method of calculation adopted in the paper cannot be applied to this cone angle without modification since i_θ would be infinite.

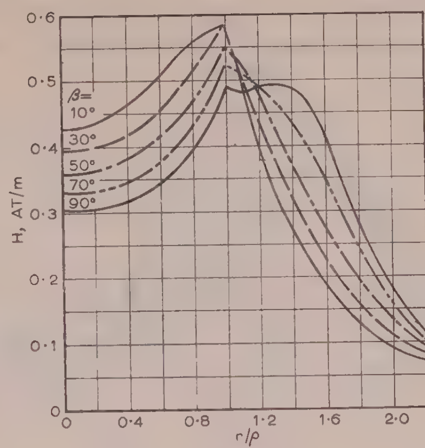


Fig. 7.—$\hat{H}_r$ due to complete winding at different cone angles.

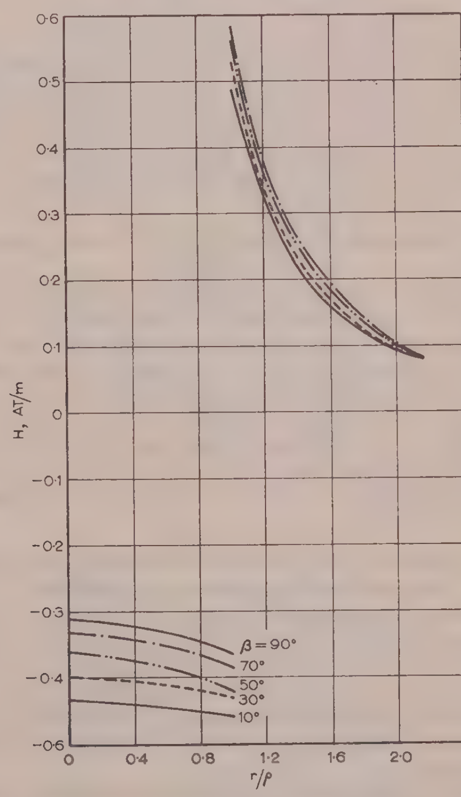


Fig. 8.—$\hat{H}_\theta$ due to complete winding at different cone angles.

Figs. 7–9 throw an interesting light on the variation of stray loss with cone angle. The loss will depend on the magnitude of the field and on the surface area of the end-plate. The area at a particular radius is proportional to the radius, and hence the field components at large radii will contribute more to the losses than those at small radii. The inner radius of the core

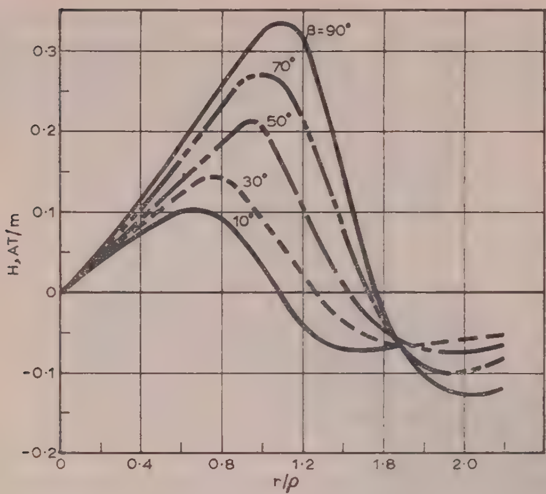


Fig. 9.—$\hat{H}_z$ at different cone angles.

end-plate is at about $r/\rho = \frac{3}{4}$. The mass of the core end-plate is situated at $r/\rho > 1 \cdot 2$. At such radii H_θ is substantially independent of cone angle, but both H_r and H_z increase with increase of cone angle. Furthermore, the maxima of H_r and H_z occur at larger radii as the cone angle is increased. Thus a greater cone angle would be expected to give greater losses, which is in accordance with test results. (But see also Section 5.5.)

(5.4) Variation of Magnetic Field with Chording Angle of Stator Winding

The line current density due to each layer of the stator winding is $\frac{1}{2}\hat{\imath}_s \cos(\omega t - \alpha)$. Hence the line density due to both layers is $\hat{\imath}_s \sin p\mu \cos(\omega t - \alpha)$, the coil pitch being 2μ. The variation of the magnetic field with μ will depend on the magnitude of $\sin \mu$ and also on the variation with μ of $\hat{\imath}_r$, $\hat{\imath}_\theta$ and $\hat{\imath}_z$. It was found that the field varied dominantly as $\sin \mu$. Thus for any particular value of the current line density the field is independent of chording angle. This is an important conclusion because it eliminates one of the two variables in the design of a conical end-winding.

(5.5) Variation of Magnetic Field with Distance of Inclined Part of End-Winding from Core End-Plate

Fig. 10 shows the variation of magnetic field, H_z, as the parameter Z is changed, i.e. as the axial length of the end-winding is changed. H_θ and H_r are practically unchanged, because they include the effect of a considerable length of slot current. H_z is entirely due to the inclined portion of the end-winding and is considerably reduced as this portion is moved away from the core end-plate.

It should be noted that in Section 5.3 we considered a change of cone angle with constant Z. In a practical design, however, Z will have to be longer for lower values of cone angle in order to maintain insulation clearances. Thus the curves of Figs. 7–9 and Fig. 10 should be considered together. The decrease in stray loss observed at smaller cone angles will be partly due to the larger values of Z.

(6) ROTOR WINDING

(6.1) Description of Rotor Winding

The rotor winding of a typical turbo-generator is shown in Fig. 11. The winding consists of an axial slot portion of straight conductors grouped in bands between each pole centre and of an end section which forms the complete coils. Fig. 12 shows a development of the winding on a cylinder of radius ρ_R.

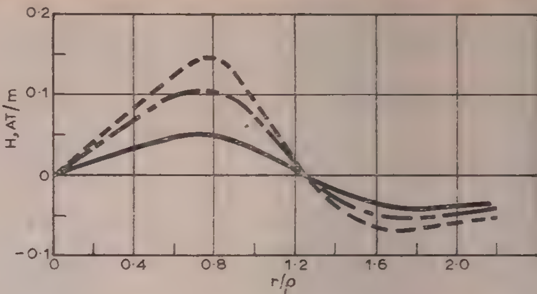


Fig. 10.—Variation of H_z with distance of inclined part of end-winding from core end-plate.

--- ---- $Z = 0 \cdot 11$ m.
—·—·— $Z = 0 \cdot 16$ m.
——— $Z = 0 \cdot 21$ m.

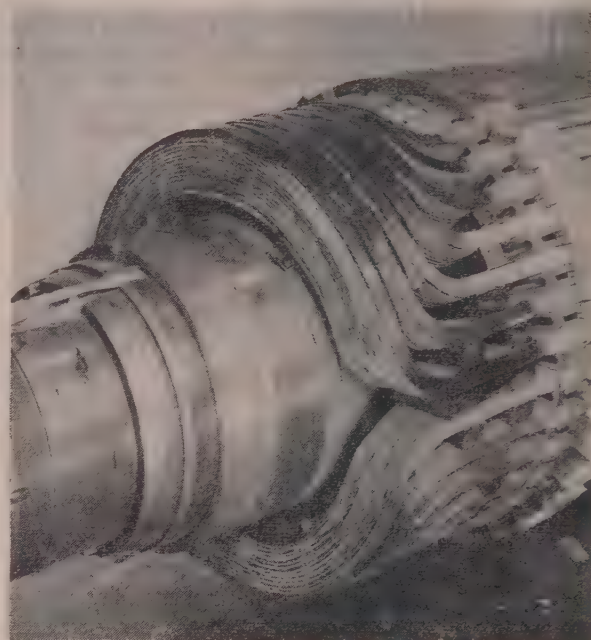


Fig. 11.—Rotor end-winding.

(6.2) Simplified Representation of Rotor Winding

We shall represent the actual current distribution by a tubular current sheet of radius ρ_R. In the slot portion the current flow will be axial and in the end section there will be both axial and circumferential current. As in the case of the stator winding we shall consider only the fundamental components of current.

At any point the magnitude of this fundamental will be proportional to the sine of the angle covered by the current band, i.e. i_z will vary as $\sin x\delta$ and i_θ as $\cos x\delta$ (see Fig. 12). In the slot portion x is unity and in the end section x is less than unity. Thus, if the magnitude of the fundamental component of current line density is $\hat{\imath}_R$ in the slot portion, we have in the end section

$$\hat{\imath}_z = \hat{\imath}_R \frac{\sin x\delta}{\sin \delta}$$

and $$\hat{\imath}_\theta = \hat{\imath}_R \frac{\rho_R \delta}{L_R} \frac{\cos x\delta}{\sin \delta}$$

The rotor winding can thus be represented by a single tube of axial current for the slot portion and a number of tubes for the

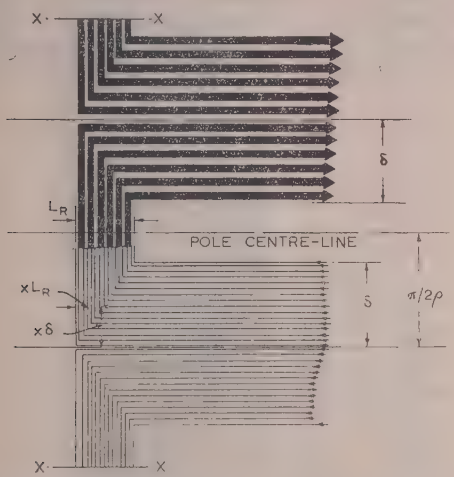


Fig. 12.—Development of rotor winding on the surface of a cylinder.

Top.—Actual winding. Bottom.—Supposed current distribution.

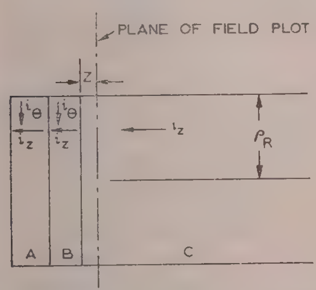


Fig. 13.—Simplified representation of rotor winding.

end sections. We use two such tubes, shown in Fig. 13 as tubes A and B. The magnitude of current in these tubes is taken as that on the rotor at their mid-points.

(6.3) Computed Results for Rotor Winding

For the generator considered in the paper the relevant rotor dimensions are as shown in Table 4.

Table 4

PARAMETERS OF ROTOR WINDINGS OF 6·5 MW GENERATOR

$$\delta = 1{\cdot}2 \text{ rad}$$
$$\rho_R = 0{\cdot}242 \text{ m}$$
$$L_R = 0{\cdot}222 \text{ m}$$
$$Z_R = -0{\cdot}015 \text{ m}$$

(see Figs. 12 and 13).

The negative sign in Z_R indicates that the rotor end-winding projects inside the stator core end-plate. These dimensions give values for the tubes A, B and C of Fig. 13 as shown in Table 5.

Table 5

EQUIVALENT CURRENT SHEETS FOR ROTOR WINDING OF 6·5 MW GENERATOR

	$i_z = -i_r$	i_θ	R	ΔR	l	z
	A/m	A/m	m	m	m	m
A	0·318	1·43	0·242	0	0·055	0·150
B	0·840	0·920	0·242	0	0·055	0·040
C	1·000	0	0·242	0	0·500	−0·515

An axial length of 1 metre has been taken, as for the stator winding, in order to represent the slot portion of the winding.

The resulting values for the magnetic field of the rotor are shown in Fig. 14. In order to facilitate comparison of stator and rotor fields the magnetic fields in Fig. 14 are plotted against r/ρ, where ρ is the radius of the stator current sheet. It will be

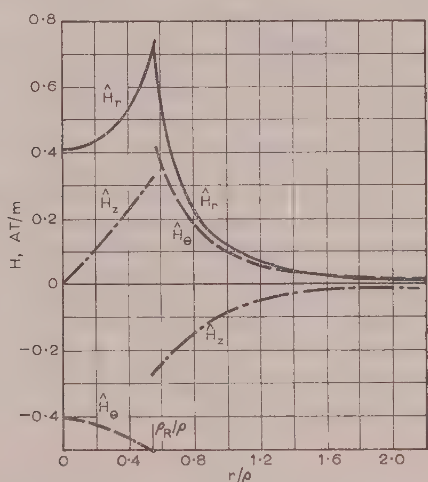


Fig. 14.—Field of rotor winding.

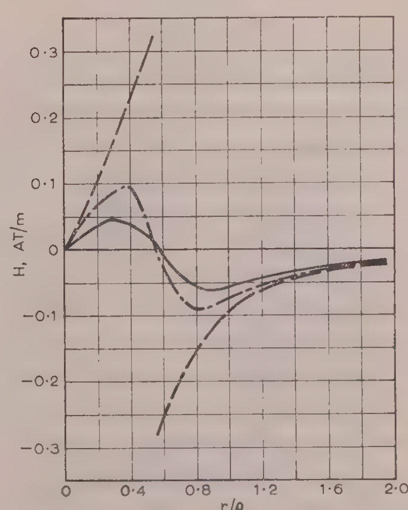


Fig. 15.—Variation of H_z with distance of rotor end-winding from core end-plate.

———— $Z = -0{\cdot}015$ m.
—·—·— $Z = 0{\cdot}035$ m.
———— $Z = 0{\cdot}085$ m.

noted that there is a discontinuity in H_z as well as in H_θ. This arises from the fact that the plane of the field plot intersects the rotor winding where it carries not only axial but also circumferential current.

The machine considered here has a rotor current of 265 amp at full load and rated power factor. There are 168 turns per pole. This corresponds to a fundamental current line density, $\hat{\imath}_R$, of $1{\cdot}8 \times 10^5$ A/m. The ordinates in Fig. 14 must therefore be multiplied by this number to give the full-load field of the rotor.

(6.3.1) Variation of Magnetic Field with Distance of Rotor End-Winding from Core End-Plate.

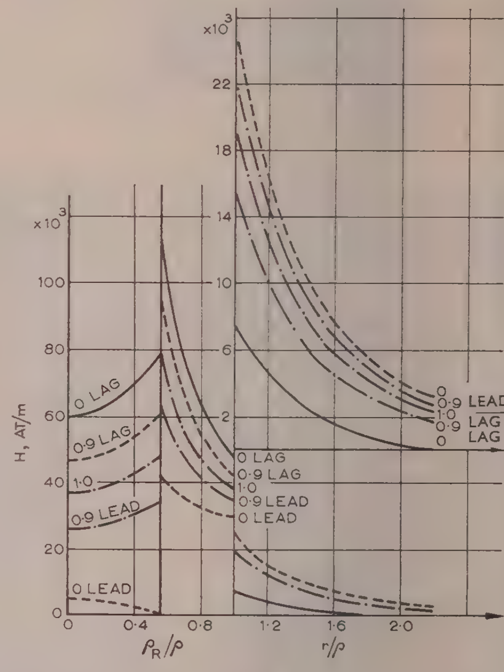
H_r and H_θ are practically unchanged with variation of Z. This is to be expected, because they both depend on the long slot portion. H_z is, however, considerably reduced as Z is increased. This is shown in Fig. 15.

(7) ADDITION OF STATOR AND ROTOR FIELDS AT VARIOUS POWER FACTORS

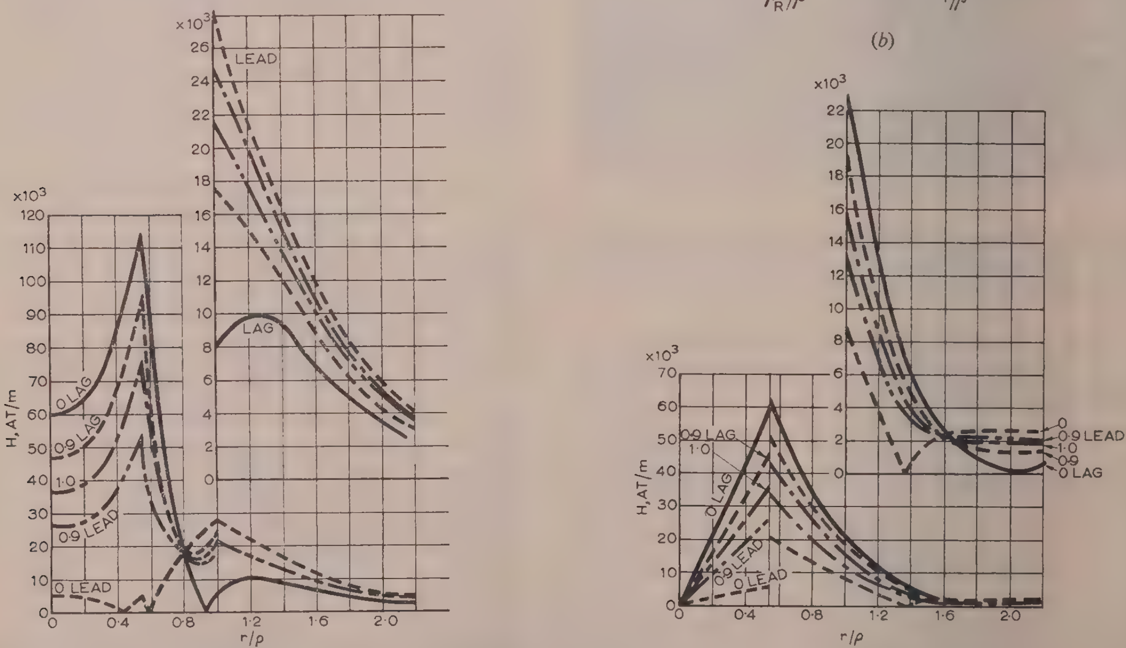
The magnetic-field components of the stator winding shown in Fig. 6 can be combined with the magnetic field of the rotor winding shown in Fig. 14. It is of particular interest to examine the resultant field at various power factors, since turbo-generators have particularly high stray losses at leading power factors. These losses can cause serious overheating.

For a machine operating at constant apparent power it is easy to find the stator and rotor fields at any power factor and to determine the phase angle between these fields. The resultant field can then be obtained by vector addition. This was done for the generator considered in the paper operating at its full rating of 9·2 MVA. The results are plotted in Fig. 16.

It will be noted from Fig. 16 that at small radii a lagging power factor results in a stronger field. But it is the field at larger radii that is of particular interest, because it is this which causes the eddy-current loss in the core end-plate. Over most of the region of the end-plate (i.e. $r/\rho > 0{\cdot}8$) it is a leading power factor which gives the stronger field. This is consistent with test results. Fig. 17 shows the effect of power factor on the components of field in the region of the bottom of the stator slots (i.e. $r/\rho = 1{\cdot}2$). These results should be compared with Fig. 6 of Reference 5, which shows the variation of temperature rise with power factor. This experimental curve is of the same shape as the curves of H_r and H_θ in Fig. 17. In seeking to reduce stray losses, designers should therefore pay particular attention



(b)



(a) (c)

Fig. 16.—Field due to combined stator and rotor windings at different power factors and constant apparent power.

(a) Radial component. (b) Circumferential component. (c) Axial component.

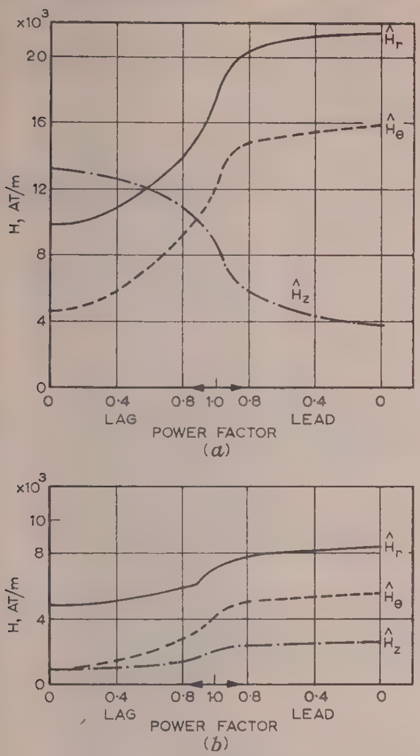


Fig. 17.—Variation of total field with power factor.

(a) At a radius corresponding to the bottom of the stator slots: $r/\rho = 1\cdot2$. (b) At a large radius: $r/\rho = 1\cdot8$.

to a reduction of H_r and H_θ. The axial component, H_z, seems to be of less importance at leading power factors.

It is at first sight strange that the field should be stronger at leading power factors, when the rotor current is small. It must, however, be borne in mind that the resultant field of Fig. 17 is obtained by vector addition of the rotor field and the stator field. The angle between the vectors is such that this results effectively in an arithmetical subtraction. Moreover the radial field, H_r, must be constant at the air-gap radius because the machine is operating at constant apparent power. This explains the crossing-over of the curves in Fig. 16, so that the field beyond the air-gap radius changes in the opposite manner to that within it.

(8) EXPERIMENTAL RESULTS WITH MODEL WINDING

A model of the stator winding of the 6·5 MW machine used in these calculations was constructed to a scale of 1 : 3. A small 3-dimensional search coil was used, connected to a valve voltmeter to explore the field of the model winding. The field components were measured on a plane corresponding to the surface of the core end-plate. These measured values are plotted in Fig. 18 and for comparison the calculated values are also given. It will be seen that there is reasonable agreement. The gap in the measured curves is due to the fact that the winding interfered with the search coil in this region.

(9) ACKNOWLEDGMENTS

The authors wish to acknowledge the encouragement given to them by Sir Willis Jackson, Director of Research and Education, A.E.I. (Manchester) Ltd. Their thanks are also due to Mr. S. Neville, Mr. E. W. Consterdine and especially to Mrs. M. Phillips, who developed the computer programme, all of whom are with A.E.I. (Manchester) Ltd.

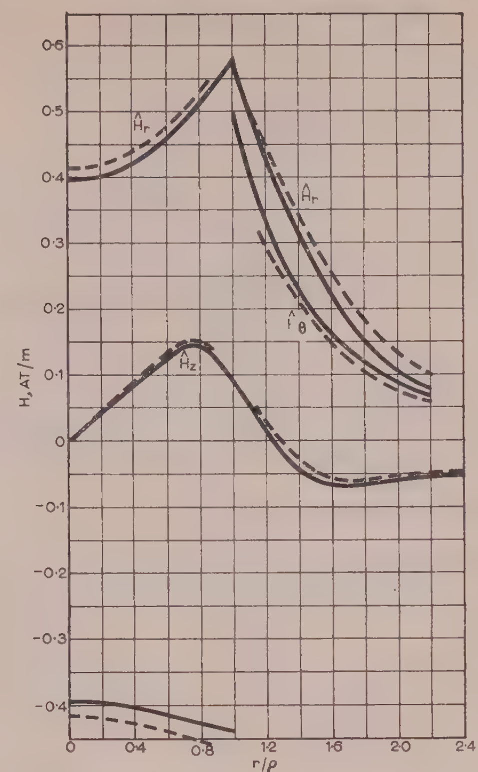


Fig. 18.—Comparison of calculated and measured values of stator field.

---- Measured.
—— Calculated.

(10) REFERENCES

(1) Hammond, P.: 'The Calculation of the Magnetic Field of Rotating Machines. Part 1.—The Field of a Tubular Current', *Proceedings I.E.E.*, Monograph No. 333, May, 1959 (**106** C, p. 158).

(2) Hammond, P.: 'Electric and Magnetic Images', *ibid.*, Monograph No. 379, May, 1960 (**107** C, p. 306).

(3) Smith, R. T.: 'End Component of Armature Leakage Reactance of Round-Rotor Generators', *Transactions of the American I.E.E.*, 1958, **77**, Part III, p. 636.

(4) Honsinger, V. B.: 'Theory of End-Winding Leakage Reactance', *ibid.*, 1959, **78**, Part III, p. 417.

(5) Mason, T. H., Aylett, P. D., and Birch, F. H.: 'Turbo-Generator Performance under Exceptional Operating Conditions', *Proceedings I.E.E.*, Paper No. 2846 S, January, 1959 (**106** A, p. 357).

(11) APPENDICES

(11.1) Distribution of Current on a Conical End-Winding

Fig. 19 shows a development of the involute end-winding on the surface of a cone. The winding is made up from a number of separate coils as shown in Fig. 2, the coil nose being neglected.

Consider the current at a general point P whose position is

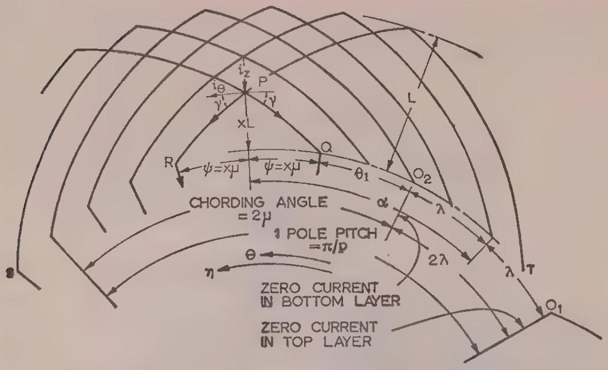


Fig. 19.—Development of end-winding on the surface of a cone.

determined by the length xL and the angle α. (All angles shown in Fig. 19 except γ and η are measured in a plane perpendicular to the axis of the machine and are proportional to the arcs shown.)

Two simplifying assumptions are made:

(*a*) The angle γ is constant, i.e. the involute has the same shape as an equi-angular spiral.

(*b*) The angle ψ is proportional to the distance xL, i.e. $\psi = x\mu$. This assumes that the involute has the shape of an Archimedean spiral.

Fig. 20 compares an involute, plotted in polar co-ordinates, with these two spirals. The spirals are chosen to be close to

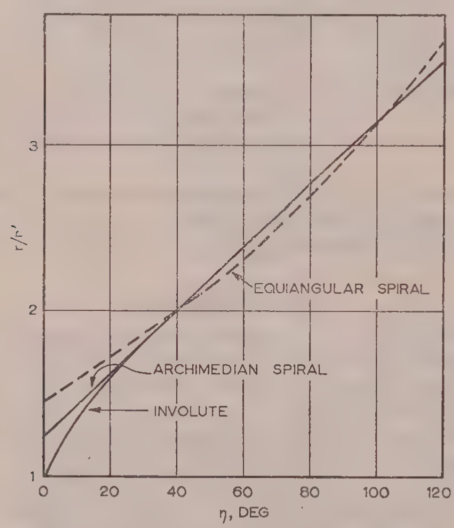


Fig. 20.—Comparison of involute with spirals.

the involute over a range of η from 25° to 120°, which is likely to be the greatest range met in an actual design of an involute coil. (The zero of η is defined with reference to the involute.) Thus, although the two assumptions are contradictory, they are both reasonable. In most cases the range of η will be much less, and closer-fitting spirals could be chosen. Having justified the two assumptions we need not consider the spirals any further.

It has already been shown in Section 3.2 that the current in each layer of the winding varies sinusoidally with the angle. Let the current in each layer at the intersection of a plane SRQT with the winding (Fig. 19) be $\hat{\imath}\sin p\theta$ and let the origins of θ be at O_1 and O_2 for the top and bottom layers, respectively.

Then the current in PQ is

$$i_{PQ} = \hat{\imath}\sin\theta_1 = \hat{\imath}\sin p\,[\alpha - (\lambda + x\mu)]$$

where $\lambda = (\pi/2p) - \mu$.

Similarly the current in PR is

$$i_{PR} = \hat{\imath}\sin p[\alpha + (\lambda + x\mu)]$$

Thus the component i_θ of the current at P is given by

$$\begin{aligned} i_\theta &= i_{PR}\cos\gamma - i_{PQ}\cos\gamma \\ &= 2\,\hat{\imath}\cos\gamma\cos p\alpha\sin p(\lambda + x\mu) \\ &= \hat{\imath}_\theta\cos p\alpha\cos p(1 - x)\mu \quad . \quad . \quad . \quad . \quad (1) \end{aligned}$$

where $\hat{\imath}_\theta$ is a constant.

Similarly $\quad i_z = \hat{\imath}_z\sin p\alpha\sin p(1 - x)\mu \quad . \quad . \quad . \quad . \quad (2)$

Eqns. (1) and (2) give the current for different positions of P.

The condition for continuity of current over half a pole pitch is

$$\int_0^{\pi/2p}\hat{\imath}_s\rho\sin p\mu\sin p\alpha d\alpha = \int_0^{\pi/2p}\hat{\imath}_z R\sin p\alpha\sin p(1 - x)\mu d\alpha + \int_0^x \hat{\imath}_\theta L\cos\beta\cos p(1 - x)\mu dx$$

Hence $\hat{\imath}_s\rho\sin p\mu = \hat{\imath}_z R\sin p(1 - x)\mu + \dfrac{\hat{\imath}_\theta L\cos\beta}{\mu}[\sin p\mu - \sin p(1 - x)\mu]$

This must be true for all values of x. Hence

$$\hat{\imath}_\theta = \frac{\hat{\imath}_s\rho\mu}{L\cos\beta} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and

$$\hat{\imath}_z = \frac{\hat{\imath}_s\rho}{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Eqns. (1)–(4) determine the currents along the generators of the cone, i_z, and perpendicular to the generators, i_θ. If the cone is replaced by a stepped arrangement of tubes and discs, the axial current will be i_z and the circumferential current i_θ. The radial current, i_r, will be equal in magnitude to i_z, but, being directed inwards, it must be taken as negative.

If the end-winding is represented by N tubes and discs, it can readily be shown by reference to Fig. 21 that

$$x = \frac{2n + 1}{2N} \qquad n = 0, 1, \ldots, N - 1$$

$$R = \rho + xL\sin\beta$$

$$l = \frac{1}{2N}L\cos\beta$$

$$\Delta R = \frac{1}{N}L\sin\beta$$

$$z = Z + xL\cos\beta$$

(11.2) Magnetic Field of Tubular Current Sheets

Referring to Fig. 4, we consider three types of current distribution:

(*a*) Axial current of line density, $\hat{\imath}_z\sin p\alpha\sin\omega t$.
(*b*) Circumferential current of line density $\hat{\imath}_\theta\cos p\alpha\sin\omega t$.
(*c*) Radial current of line density $\hat{\imath}_r\sin p\alpha\sin\omega t$.

Currents (*a*) and (*b*) are distributed over the surfaces of tubes each of radius R and length $2l$. Current (*c*) is distributed on thin annular discs each of mean radius R and radial depth ΔR.

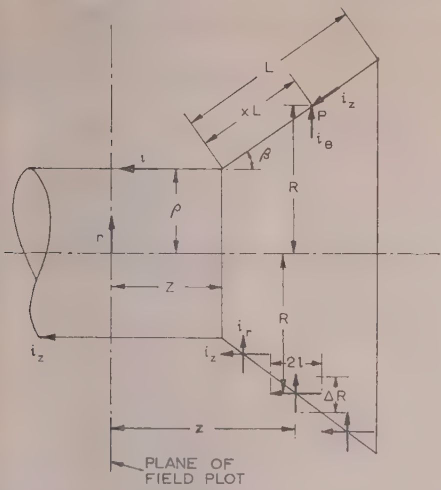


Fig. 21.—Relating to the determination of current on a cone.

These single isolated current sheets are replaced by an infinite succession of equal and oppositely directed coaxial current sheets spaced at a distance g such that mutual effects will be negligible. The currents can then be expressed by Fourier series.

For currents (a) and (b),

$$i_{z,\theta} = \frac{4}{\pi}\hat{\imath}_{z,\theta}\sum_{s=1}^{\infty}\frac{1}{s}\sin sbl\cos sbz \quad . \quad . \quad . \quad . \quad (5)$$

For current (c),

$$i_r = \frac{2bR}{\pi}\hat{\imath}_r\sum_{s=1}^{\infty}\cos sbz \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where s is odd.

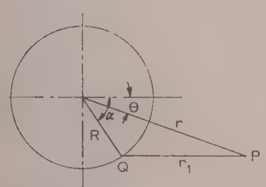


Fig. 22.—Relating to the vector potential of a tubular current.

Refer now to Fig. 22 and consider the case when $r > R$. Using eqn. (13) of Part 1 of the paper,[1] the vector potential at P due to an axial tubular current is

$$A_z = \frac{4}{\pi}\mu_0\hat{\imath}_z R\sin p\theta\sin\omega t\sum_{s=1}^{\infty}\frac{1}{s}K_p(sbr)I_p(sbR)\sin sbl\cos sbz \quad . \quad (7)$$

Using the relation $\mu_0 H = \text{curl } A$, we have

$$H_z = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

$$H_r = \frac{4p}{\pi r}\hat{\imath}_z R\cos p\theta\sin\omega t\sum_{s=1}^{\infty}\frac{1}{s}K_p(sbr)I_p(sbR)\sin sbl\cos sbz \quad . \quad (9)$$

$$H_\theta = -\frac{4b}{\pi}\hat{\imath}_z R\sin p\theta\sin\omega t\sum_{s=1}^{\infty}K_p'(sbr)I_p(sbR)\sin sbl\cos sbz \quad . \quad . \quad . \quad . \quad (10)$$

Using eqns. (17) and (18) of Part 1 we have the vector potential of a circumferential current given by

$$A_r = -\frac{2}{\pi}\mu_0\hat{\imath}_\theta R\sin p\theta\sin\omega t\sum_{s=1}^{\infty}\frac{1}{s}[K_{p+1}(sbr)I_{p+1}(sbR) - K_{p-1}(sbr)I_{p-1}(sbR)]\sin sbl\cos sbz \quad . \quad (11)$$

and

$$A_\theta = \frac{2}{\pi}\mu_0\hat{\imath}_\theta R\cos p\theta\sin\omega t\sum_{s=1}^{\infty}\frac{1}{s}[K_{p+1}(sbr)I_{p+1}(sbR) + K_{p-1}(sbr)I_{p-1}(sbR)]\sin sbl\cos sbz \quad . \quad (12)$$

whence the magnetic field of a circumferential current is given by

$$H_r = \frac{2b}{\pi}\hat{\imath}_\theta R\cos p\theta\sin\omega t\sum_{s=1}^{\infty}[K_{p+1}(sbr)I_{p+1}(sbR) + K_{p-1}(sbr)I_{p-1}(sbR)]\sin sbl\sin sbz \quad . \quad (13)$$

$$H_\theta = \frac{2b}{\pi}\hat{\imath}_\theta R\sin p\theta\sin\omega t\sum_{s=1}^{\infty}[K_{p+1}(sbr)I_{p+1}(sbR) - K_{p-1}(sbr)I_{p-1}(sbR)]\sin sbl\sin sbz \quad . \quad (14)$$

$$H_z = -\frac{4b}{\pi}\hat{\imath}_\theta R\cos p\theta\sin\omega t\sum_{s=1}^{\infty}K_p(sbr)I_p'(sbR)\sin sbl\cos sbz \quad . \quad . \quad . \quad . \quad (15)$$

The vector potential of a radial current can be obtained in a similar manner:

$$A_r = -\frac{b}{\pi}\mu_0\hat{\imath}_r R\Delta R\sin p\theta\sin\omega t\sum_{s=1}^{\infty}[K_{p+1}(sbr)I_{p+1}(sbR) + K_{p-1}(sbr)I_{p-1}(sbR)]\cos sbz \quad . \quad (16)$$

$$A_\theta = \frac{b}{\pi}\mu_0\hat{\imath}_r R\Delta R\cos p\theta\sin\omega t\sum_{s=1}^{\infty}[K_{p+1}(sbr)I_{p+1}(sbR) - K_{p-1}(sbr)I_{p-1}(sbR)]\cos sbz \quad . \quad (17)$$

whence the magnetic field of a radial current is given by

$$H_r = -\frac{b^2}{\pi}\hat{\imath}_r R\Delta R\cos p\theta\sin\omega t\sum_{s=1}^{\infty}s[K_{p+1}(sbr)I_{p+1}(sbR) - K_{p-1}(sbr)I_{p-1}(sbR)]\sin sbz \quad . \quad (18)$$

$$H_\theta = -\frac{b^2}{\pi}\hat{\imath}_r R\Delta R\sin p\theta\sin\omega t\sum_{s=1}^{\infty}s[K_{p+1}(sbr)I_{p+1}(sbR) + K_{p-1}(sbr)I_{p-1}(sbR)]\sin sbz \quad . \quad (19)$$

$$H_z = -\frac{2pb}{\pi}\hat{\imath}_r\Delta R\cos p\theta\sin\omega t\sum_{s=1}^{\infty}K_p(sbr)I_p(sbR)\cos sbz \quad . \quad (20)$$

The total magnetic field can be obtained by adding the components. If we write $\cos(\omega t - p\theta)$ for $\sin p\theta\sin\omega t$ we obtain the following expressions for $r > R$:

$$\hat{H}_z = \frac{H_z}{\sin(\omega t - p\theta)} = -\frac{4b}{\pi}\hat{\imath}_\theta R\sum_{s=1}^{\infty}K_p(sbr)I_p'(sbR)\sin sbl\cos sbz - \frac{2pb}{\pi}\hat{\imath}_r\Delta R\sum_{s=1}^{\infty}K_p(sbr)I_p(sbR)\cos sbz \quad . \quad . \quad (21)$$

$$\hat{H}_\theta = \frac{H_\theta}{\cos(\omega t - p\theta)} = -\frac{4b}{\pi}\hat{\imath}_z R\sum_{s=1}^{\infty}K_p'(sbr)I_p(sbR)\sin sbl\cos sbz +$$

$$+\frac{2b}{\pi}i_\theta R\sum_{s=1}^{\infty}[\mathrm{K}_{p+1}(sbr)\mathrm{I}_{p+1}(sbR)$$
$$-\mathrm{K}_{p-1}(sbr)\mathrm{I}_{p-1}(sbR)]\sin sbl\sin sbz$$
$$-\frac{b^2}{\pi}i_rR\Delta R\sum_{s=1}^{\infty}s[\mathrm{K}_{p+1}(sbr)\mathrm{I}_{p+1}(sbR)$$
$$+\mathrm{K}_{p-1}(sbr)\mathrm{I}_{p-1}(sbR)]\sin sbz \quad . \quad (22)$$

$$\hat{H}_z=\frac{H_z}{\sin(\omega t-p\theta)}$$
$$=\frac{4p}{\pi r}i_zR\sum_{s=1}^{\infty}\frac{1}{s}\mathrm{K}_p(sbr)\mathrm{I}_p(sbR)\sin sbl\cos sbz+$$
$$+\frac{2b}{\pi}i_\theta R\sum_{s=1}^{\infty}[\mathrm{K}_{p+1}(sbr)\mathrm{I}_{p+1}(sbR)$$
$$+\mathrm{K}_{p-1}(sbr)\mathrm{I}_{p-1}(sbR)]\sin sbl\sin sbz$$
$$-\frac{b^2}{\pi}i_rR\Delta R\sum_{s=1}^{\infty}s[\mathrm{K}_{p+1}(sbr)\mathrm{I}_{p+1}(sbR)$$
$$-\mathrm{K}_{p-1}(sbr)\mathrm{I}_{p-1}(sbR)]\sin sbz \quad . \quad (23)$$

The expressions for the magnetic field when $r < R$ can be obtained by transposing r and R in the argument of the Bessel functions of eqns. (21)–(23).

[The discussion on the above paper will be found on page 549.]

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THE MAGNETIC FIELD OF THE END-WINDINGS OF TURBO-GENERATORS

By P. J. LAWRENSON, M.Sc., Graduate.

(The paper was first received 19th May, and in revised form 14th October, 1960. It was published in March, 1961, and was read before the SUPPLY SECTION 12th April, 1961.)

SUMMARY

An investigation of the magnetic field generated by the currents in the stator end-windings of a 3-phase 2-pole turbo-generator is described. It includes an examination of the influence of winding design, namely the effects of cone angle, straight projection and coil pitch, of the influence of the air-gap, and also of the permeability, or eddy-current screening, of the core end-plate.

The simple and accurate method which is used to calculate the field of the stator currents, and which can be used for a circuit of any shape, is described. The effect of the air-gap is represented by a fictitious conductor, and the influence of the end-plate is accounted for by use of the method of images. Results are presented for the magnitude and phase of the fundamental and harmonic waves of the rotating fields on the end-plate and rotor-coil retaining-ring surfaces.

From the results the following points appear:

(*a*) The predominant loss-producing component of the field at the end-plate surface arises from the fringing at the end of the air-gap.

(*b*) In order to reduce loss-producing components of the field at the end-plate due to the winding the cone angle should be made small and the straight projection large.

(*c*) The use of a non-magnetic end-plate reduces the axial component of the field.

(*d*) The use of eddy-current screening, whilst eliminating the axial components, increases the radial components.

(*e*) Near the winding and the air-gap, the field contains a high proportion of harmonic components which induce loss in the rotor-coil retaining ring. They increase in magnitude with increases in the straight projection of the winding and the air-gap magnetomotive force.

(*f*) Changes in coil pitch do not significantly influence either the fundamental or the harmonics of the end field.

(1) INTRODUCTION

The need for careful investigation of the effects of the magnetic fields generated by the currents in the end-windings of turbo-generators (and other large electrical machines) has long been appreciated,[1–3] and during the last 10–15 years, because of the enormous increases in electrical loadings which have been made, this need has become more urgent. The stray fields have two particularly important effects. First, they produce, in all conducting parts of the end structure, eddy-current and power losses which not only represent a large part of the total loss in the machine but also are liable to cause damage owing to overheating in localized regions; examinations of eddy-current effects in certain parts of the machine, e.g. in the stator winding[1, 4, 5] or in the end-plate teeth,[6] have been described in many papers. Secondly, the stray fields result in the development, on the end-winding itself, of forces which can also cause severe damage during short-circuit conditions; this subject, too, has been discussed in a number of papers.[7–9]

The complete analysis of the magnetic field in the end regions of the machine is an extremely difficult one. Not only is the field generated by a very complicated pattern of primary currents but also it is modified by boundaries which are of very complicated shape, which have varying values of permeability, and which are the seat of modifying eddy currents. Consideration of these features indicates that no exact analytical or numerical solution for the field is possible at present or foreseeable in the future. Nevertheless, by making certain simplifying assumptions with regard to the form of the enclosing boundaries, it is possible to calculate a considerable amount of information which can provide useful guidance to designers. This includes, for example, a knowledge of the general distribution of field in the end space and of the forces experienced by the winding.

References 5, 7, 8 and 9 are typical of previous theoretical work on the end-field problem and in all of them the boundary surfaces, when considered, are represented as being plane. The assumptions made in these works with regard to the form of the windings vary more widely and, in general, the representations of the winding shapes have been inadequate; only the one

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described in Reference 9 is satisfactory, and in that treatment the boundary effects are neglected. Other representations have been unsuited to the analysis of 2-pole windings (which are the most important), to the determination of forces (which are primarily functions of the actual coil geometry) or to the examination of the effects of changing the design of the winding. Previous work has been deficient also in that no general examination has been made of the distributions of flux on the surfaces of conducting parts in which eddy-current losses occur.

In the present paper an investigation of this general distribution of field exterior to the end-structure is described. A method by which the true shape of the current paths in the stator (or any other winding) can be accounted for very simply is presented. Boundary effects are represented using the method of images and a fictitious conductor in the air-gap. In doing this care is taken to ensure continuity of the currents in the image circuits, for, as indicated by Carpenter[10] and Hammond,[11] failure to do this results in inadequate image representations of the types used, for example, by Harrington[7] and Douglas.[12] The general influences upon the field of the air-gap, of the permeability and eddy-current screening of the end-plate and of changes in the winding design are investigated. Results are presented, in terms of the magnitude and phase of the fundamental and harmonic waves, showing the distribution of field over the whole of the end-plate and the rotor-coil retaining ring.

The calculation of eddy-current loss from the field is not attempted, but on the basis that the loss in a region is proportional (in some way) to the magnitude of the appropriate components of field there, it is possible to make, from the results of the field calculation, useful deductions about the loss.

Apart from the fields exterior to the end surfaces of the machine there are additional loss-producing components developed inside the conducting parts. For example, the end-plate is effectively a thick lamination of the core and it contains very large radial and tangential fields of the same order as those in the rest of the core. These fields produce eddy currents in addition to those due to the fields on the surface of the end-plate. However, it is not within the scope of the present paper to consider such fields, and attention is concentrated on the fields outside the end structure.

The windings on which the investigation is based are designed for a 6·5 MW turbo-generator having a core length of 1·6 m and a stator bore 0·66 m. The results obtained may be modified to apply to windings of other sizes by use of a scale factor: at any given point with respect to the winding, the field strength is inversely proportional to the size and directly proportional to the current loading. Strictly, this is true only if all the windings have the same proportions, but in practice the deviations from this condition are so slight that they may be neglected.

The method of calculation described here is excellently suited to an examination of the distribution of force on the winding and of the inductances of the winding (since essentially these are functions of the actual shape of the winding) and it is hoped to present results in a later paper.

(2) METHOD OF CALCULATING FIELD STRENGTH

(2.1) Introduction

In general, the magnetic field of a current filament of any shape can be found only by numerical integration. In an effort to simplify this process Halacsy devised a graphical method[13, 14] in which the integration is performed in the measurement of certain areas using a planimeter. Young and Tompsett[9] developed this method in a manner more suited to present-day computational methods by expressing the area as an integral which is evaluated numerically. It should be noted, however, that this method is merely a roundabout approach to direct numerical integration with the Biot–Savart law and, as described, requires also the determination of an equation of a curve having approximately the shape of the filament under investigation.

(2.2) Method

The method used here is to divide the filament, due to which the field is required, into such a number of connected, small straight elements as represent its true shape very closely. The field at any point is found as the vector sum of the components of the field due to all the elements of the filament. These components are expressed simply in terms of the end co-ordinates of each element and the co-ordinates of the point of interest.

This method has distinct advantages over previous treatments: it can be used immediately for any shape of coil; it can be made as accurate as is desired; and it is ideally suited for use with a digital computer. In connection with this last point it should be noted that a single programme serves for all shapes of filament because the only information required for the calculation consists of the co-ordinates of a series of points on the filament.

In Fig. 1 is shown a typical element AB (of some filament) with end co-ordinates $(x, y, z)_n$ and $(x, y, z)_{n+1}$, and a point, F,

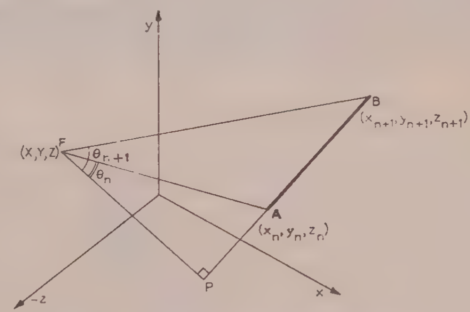

Fig. 1.—Typical straight current-element.

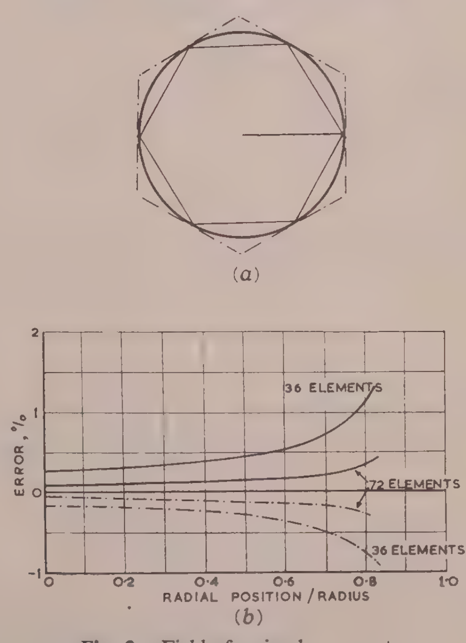

Fig. 2.—Field of a circular current.

(a) Polygonal representation of circle.
(b) Error in the axial field at the plane of the current.
—·—·— Outer polygon.
———— Inner polygon.

with co-ordinates (X, Y, Z). The field strength, H, at any point, F, is obtained using the Biot–Savart law and integrating between A and B. It has a magnitude given by

$$H = \frac{1}{4\pi}\frac{i}{\mathrm{FP}}(\sin\theta_{n+1} - \sin\theta_n) \text{ ampere-turns/metre} \quad . \quad (1)$$

where i is the element current in amperes, FP is the normal from F on the element or its projection, θ_n is the angle PFA and θ_{n+1} is the angle PFB. The direction of the field at F is normal to the plane ABF and its components in any required directions are found from a knowledge of the direction cosines of the normal to ABF. Expressions for the components parallel to the axes are derived in Section 8.1. The direction of the current is fixed, having reference to the sense of the axes, by the direction of progression round the triangle ABF in forming the differences between co-ordinates for pairs of points from A, B and F; for a left-handed set of axes and progression A to B to F (i.e. forming $x_n - x_{n+1}, \ldots x_{n+1} - X, \ldots X - x_n, \ldots$) current flows from A to B, and the expressions for field strength give the appropriate field directions.

(2.3) Accuracy

Since the accuracy with which a coil may be represented in this way is dependent upon the number of straight elements used to build up the shape and the distance of the observer from the coil, general discussion of it is not feasible. However, Fig. 2 gives, as an example, the variation and degree of accuracy to be expected in the case of a circular current. The circle may be represented by either of two polygons, one inside it or one outside it, as in Fig. 2(*a*). For both these representations, and polygons having 36 and 72 sides, calculation has been made of the axial field in the plane of the polygons along the radius shown. The errors in these fields, as a percentage of the exact values for the circle, are plotted in Fig. 2(*b*). The range of the curves is limited by the inadequacy of elliptic-function Tables which are required to calculate the exact field of the circle. At the centre of the circle the error never exceeds 0·25% even when only 36 segments are used.

(2.4) Field of a Coil

The coils of a modern turbo-generator end-winding are all alike and have the form of an involute laid upon the surface of a cone. The coil used for most of the investigation spans 15 out of 18 slot pitches per pole (i.e. 150°) and has a cone semi-angle of 30°. Details of it are reproduced, from the manufacturing drawing, in Fig. 3; (*a*) is a developed view of the coil, and (*b*) a conventional section in an axial plane through the winding.

In the calculation of its field, the coil current is assumed

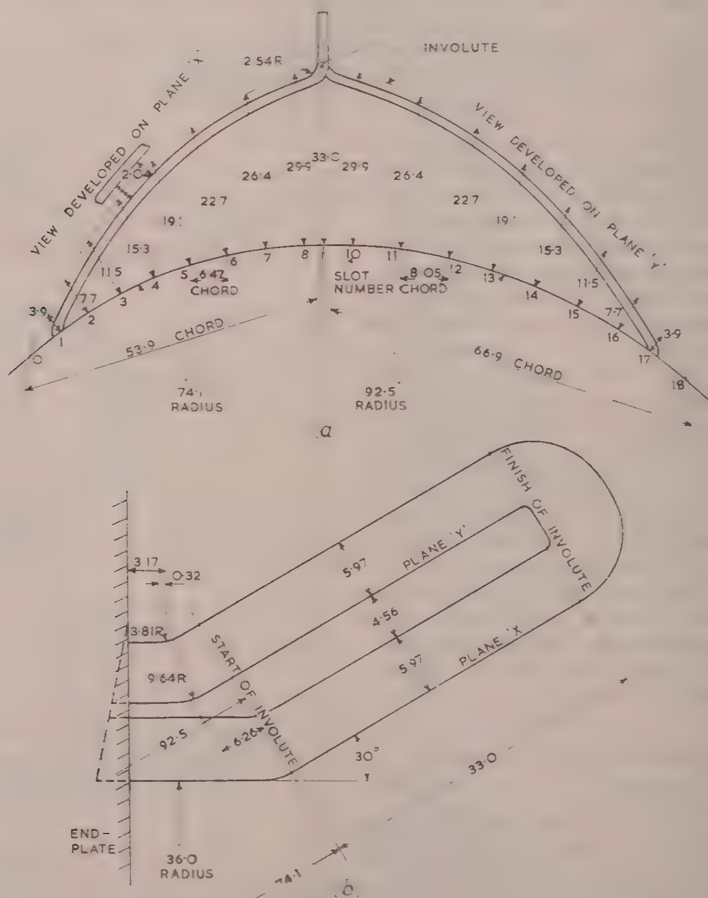

Fig. 3.—Reproduction of the manufacturing drawing for an involute stator coil.

(*a*) Developed view.
(*b*) Conventional section in axial plane.
Linear dimensions are in metres × 10^2.
Scale of (*b*) is that of (*a*) × 2.

to be concentrated in the central filament of the coil, shown by the chain line in Fig. 4; the dots of the chain represent the end points of the straight elements used to represent the filament shape. Over the involute portion there is one straight element to each slot pitch so giving a very close approximation to the shape of the central filament. The coil nose is represented by three sides of a rectangle and the full length (1·6 m) of the slot conductors is considered where appropriate. The co-ordinates of the ends of the elements are computed in the programme from simple data taken from the manufacturing drawing.

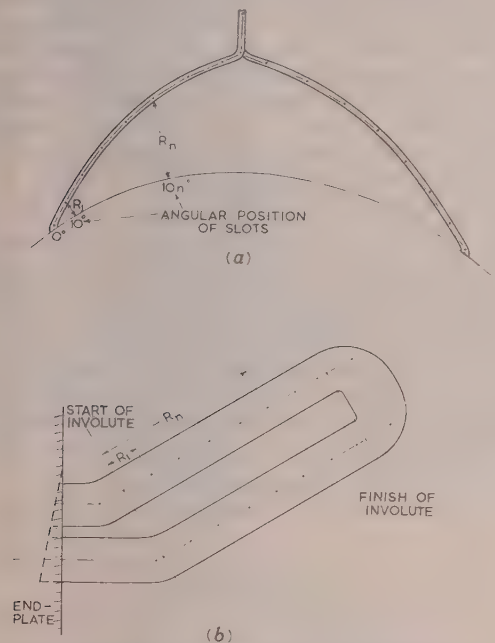

Fig. 4.—Equivalent representation of end-winding.

(a) Developed view.
(b) Sectional view.
Scale of (b) is that of(a) × 2.

The distribution of field strength at any radius about the machine axis is obtained in terms of the fundamental wave and harmonic waves (each travelling with its own sub-harmonic speed and direction) which define the field variations round the machine at the radius considered.

(2.5) Field of the Winding

Since all the coils in a winding are identical, the field of a coil group or the field of the whole winding can be obtained directly, in terms of the harmonic components of the field of the coil, simply by using the appropriate distribution factors. (It is to be noted that, whilst the field of a coil contains harmonics of all orders, the field of the complete, balanced 3-phase winding contains only those of orders $(6k \pm 1)$, where k is an integer.) The same method can also be used for conditions of unbalanced loading (of particular importance in the determination of forces), the calculation being made with the positive-, negative- and zero-phase-sequence currents.

(3) REPRESENTATION OF PHYSICAL SYSTEM

(3.1) Stator Winding

All the windings considered in this investigation were designed for the same machine and are of the balanced 2-layer type with 36 coils and 6 coils per group. They are represented for the calculation as described above. The finite cross-section of the coils could be represented by using several filaments in parallel, but in practice this was found to be unnecessary.

(3.2) Boundaries

The winding is contained in a region bounded by the rotor, the end-plate and the circumferential- and end-casings of the machine. These boundaries are actually of complicated shape; also they have different parts with widely varying permeabilities, and, further, eddy-currents flow in some parts but not others. In making the analysis it is therefore necessary to make simplifying assumptions as follows:

(a) The circumferential- and end-casings are thin and in regions of weak field. Thus, their effect, due to permeability or eddy currents which anyway tend to oppose one another, is slight and they are ignored.

(b) The fundamental wave of the field rotates at the same speed as all parts of the rotor and so induces no eddy currents in them. Thus, the effect of the rotor coil retaining ring, provided that it is non-magnetic (as is usual) can be neglected. All components of field are influenced by the permeability of the rotor body and shaft. However, the shaft, since it is relatively small and far removed from the stator winding, may be ignored and the end of the rotor body can be treated in conjunction with the core end-plate.

(c) The core end-plate is nearest to the bulk of the stator winding and its influence on the field is considerable. By representing it and the rotor end as an infinite plane surface, the influence upon the field as a whole, for different values of effective permeability, can be investigated by using the method of images.

(3.3) Use of Images

The magnetic field in air of a coil *of any shape*, carrying a current i, and influenced by the plane surface of a region having permeability μ, is given by the joint effect of the coil and an image current which replaces the permeable region. This result was first stated by Searle[15] and has recently been discussed fully by Hammond[11] and Carpenter.[10] The image current can be synthesized from two components: one has the shape and direction of the optical image (in the plane surface) of the actual coil current external to the permeable region, and the other has the position and direction of the actual current within the region. The strength of both components is $i(\mu - 1)/(\mu + 1)$. In Fig. 5(a) is shown diagrammatically the actual current of one stator coil and its image current. The field, developed by the coil and the end-plate with the surface EP, is calculated as that due to the joint action of the actual current and the image current, the effect of the latter being found using the same method as for the original coil (Section 2.4).

It is to be noted that the machine is so long that the influences of the other end-winding and end-surface are entirely negligible. (For the permeabilities considered below, the other end of the machine would have no effect regardless of its position.)

(3.4) Effective Permeability

It is not possible to account simultaneously for the actual permeability of the end-plate and the modifying effect of the eddy currents which are induced in its surface. Instead some value of effective permeability must be chosen to give the required boundary conditions, at the end-plate surface, for the field in the air.

The limiting values, $\mu = \infty$ and $\mu = 0$, give two different approaches to the form of the resultant end field. The first, with $\mu = \infty$, gives the end-field distribution that would occur with a highly permeable end-plate, assuming the modifying effect of eddy currents to be negligible; it is the distribution occurring when the fundamental and harmonic waves are stationary at the surface of the end-plate. The second, with $\mu = 0$, gives the resultant field which would occur if the eddy currents were of sufficient magnitude to prevent any flux penetrating into the

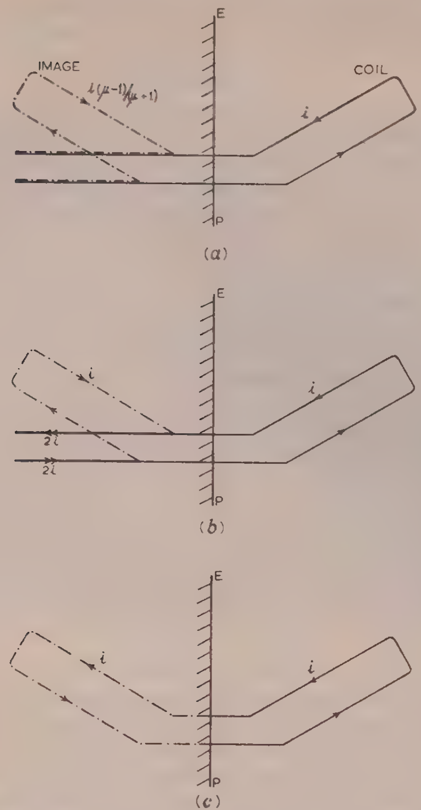

Fig. 5.—Image of a current i in a plane surface of permeability μ.

(a) General case.
(b) $\mu = \infty$.
(c) $\mu = 0$.
———— Actual current.
—·—·— Image current.

end-plate; it is attempted to achieve this condition in practice by placing copper screens on the end-plate surface. Both forms of the field distribution can be made the starting-point for a calculation of eddy-current losses, though, of course, accurate analysis is impossible. With $\mu = \infty$ the calculation is based upon the component of field normal to the conducting surface, and with $\mu = 0$ upon the components parallel to the surface. In Figs. 5(b) and (c) are shown the forms taken by the images when $\mu = \infty$ and 0, respectively. In the former the image has the strength and sign of the original current so that a double slot current is introduced. In the latter the image has the opposite sign to the original current so that the final effect is of a single closed circuit giving a field in which the end-plate surface is the plane of symmetry.

It is important to note that the above values of effective permeability are chosen so as to determine the field in the air space only. The field inside the end-plate is given by a different set of image currents, though at the end-plate surface it is continuous with the field in the air.

(3.5) Air-Gap

The representation of the machine end so far considered is as an infinite plane, continuous save for two infinitely small holes through which the parallel sides of the coil pass. There are, therefore, even when $\mu \to \infty$, radial and tangential components of field at the surface of the end-plate. Such conditions clearly do not correspond to those of reality since the air-gap between the rotor and stator has been ignored. When the circular air-gap, with the coil sides entering it, is inserted, the above radial and tangential components of field disappear and are replaced by magnetic potential differences driving flux between the rotor and stator. So far as the end-region is concerned this flux is the air-gap fringe flux, and it is important to consider how its effect may be accounted for. It should be noted that when $\mu = 0$ there can be no component of field normal to the end-surface and hence no fringe field; the above treatment ignoring the air-gap is therefore adequate in this case.

From considerations of the complexity of the boundary shape it is evident that no exact solution for the distribution of the fringe field is available. However, an approximate representation, wholly satisfactory except at points close to the gap, has been proposed by Douglas.[12] This consists simply of a fictitious current arranged to flow peripherally round the gap level with the end surface and having a magnitude sufficient to establish the required potential difference across the gap. Douglas's use of the fictitious conductor was, however, inadequate. This has been pointed out by Carpenter,[10] who considers the problem in some detail and gives the correct representation for the case when the end-surface is infinitely permeable and coil sides are diametrically opposite in the machine. The representation for the more general and practically important case of a coil spanning α mechanical radians is developed below.

Fig. 6(a) shows the axial view of a coil ABC spanning α radians and inserted in a smooth circular air-gap (indicated by the dotted lines) in the end-surface which is taken to have $\mu = \infty$. The effect of current in the coil is to drive flux from the 'stator'

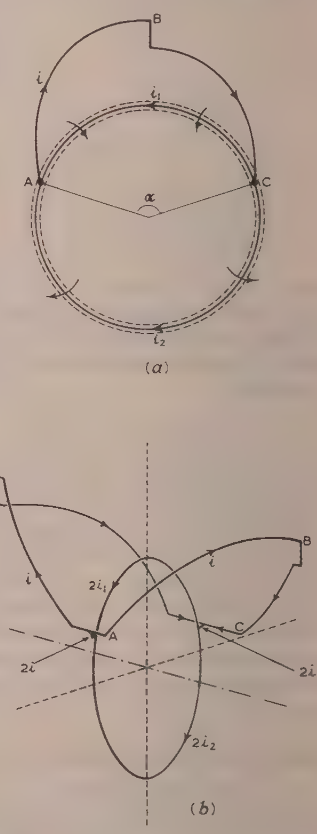

Fig. 6.—Representation of the air-gap.

(a) Axial view of coil with fictitious conductor.
(b) Perspective view of coil, fictitious conductors and images.

to the 'rotor' and back again to the 'stator', as shown by the arrows. When $\alpha = \pi$ and the coil current is i, it is easily seen that, at all points of the gap, the flux is driven by a magnetic p.d. of $i/2$ which reverses in sense at the points where the currents enter the gap. This condition can be simulated closely by causing two currents of $i/2$ to flow from C to A in paths at the position of the gap centre with *no gap* in the permeable surface. When the coil spans an angle other than π the required potential differences across the two sections of the gap differ, and for their establishment currents i_1 and i_2 flowing in the same paths as those above [see Fig. 6(*a*)] are needed. To determine i_1 and i_2 it is noted that

(*a*) Current must be continuous at A and C.

(*b*) The flux crossing the part of the gap containing the current i_1 must equal that crossing the part containing i_2 (i.e. flux must be continuous).

These conditions give, respectively, the equations

$$i_1 + i_2 = i \qquad (2)$$

and

$$i_1\alpha = i_2(2\pi - \alpha) \qquad (3)$$

from which the required currents may be simply evaluated.*

It is shown by Carpenter that, in the same way, the effect of the slots into which the currents enter can also be simulated using fictitious conductors. Doing this and replacing the effect of the infinitely permeable surface by its image circuits gives the resultant form of current distribution shown in Fig. 6(*a*). (Note that, as is necessary, there is no resultant component of field parallel to the end-surface due to this distribution.)

In the calculation of the field, using the above configuration, the circular current is replaced by 36 straight elements, one to each slot pitch.

(4) RESULTS

(4.1) Presentation

A complete description of the distribution of field strength involves a knowledge of its magnitude and phase at all points, and both of these quantities vary continuously. In the presentation of results particular attention is given to the magnitude of the field strength—plotted as the moduli of the axial, tangential and radial components—but typical curves, showing the variation of phase of the fundamental components of field, are also included. Magnitude and phase are plotted for the end-plate against radial position and for the retaining ring against axial position: the origin of radius is the machine axis, and the origin of axial position is the surface of the end-plate. The origin of phase is taken as the phase of the radial component at the centre of the end-plate. A peak current of 1 kA per coil is assumed throughout and the peak values of the fundamental and harmonic components are plotted. The two layers of the winding, in the slots, have radii of 0·385 m and 0·465 m, and the radius of the retaining ring is 0·325 m. Unless otherwise stated, the straight projection of the layer of the winding nearer to the rotor is 0·12 m and the cone angle of the winding is 30° (see Fig. 3).

It is only possible to present a summary of the results which are available. Since, in the end-plate, all harmonic components of the stator-winding field induce currents at 50 c/s, attention is concentrated primarily on the fundamental components there. At the retaining ring (with balanced current loading) the fundamental waves induce no currents and attention is concentrated on the harmonics. The effects of varying the different parameters and introducing the air-gap are described in terms of changes produced as compared with the field arising for the case of a continuous, infinitely permeable end-plate.

(4.2) General Nature of Field Distribution

Most of the main characteristics of the field distribution in the end space are unaltered by changes in permeability of the end-plate or changes in the design of the winding, and they are described in detail, for the case of an infinitely permeable end-plate, by Figs. 7–12. The main features of the distribution, as indicated by the curves, are summarized below. Those of the field on the end-plate are as follows:

(*a*) The axial component of the fundamental wave rises to a maximum at the position of the slots, beyond which it decreases rapidly to a minimum (about a third of the way across the end-plate), finally passing through a second, but much lower, peak. Its phase changes slowly near the position of the maximum but quickly

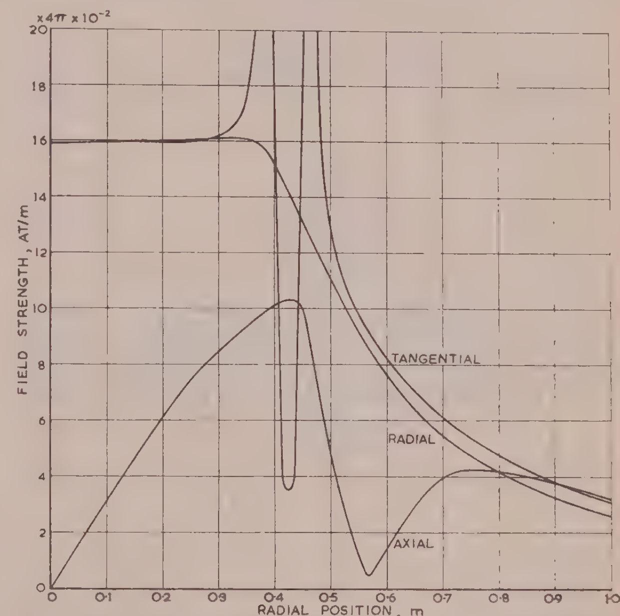

Fig. 7.—Fundamental components of field on a permeable end-plate.

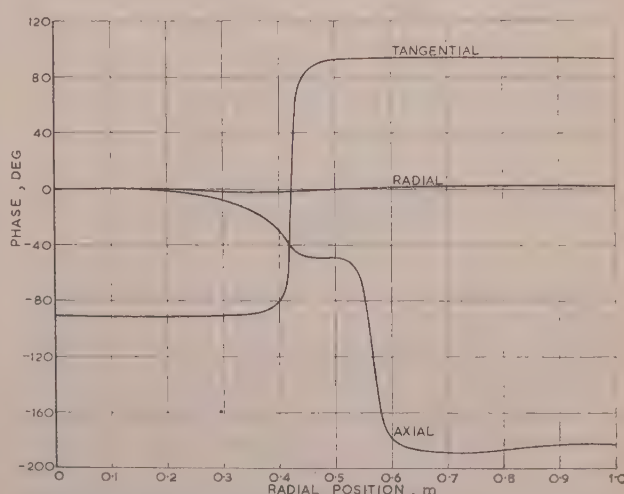

Fig. 8.—Phase of fundamental components on a permeable end-plate.

* It is to be noted that the resultant air-gap current for the complete winding is independent of the ratio i_1/i_2.

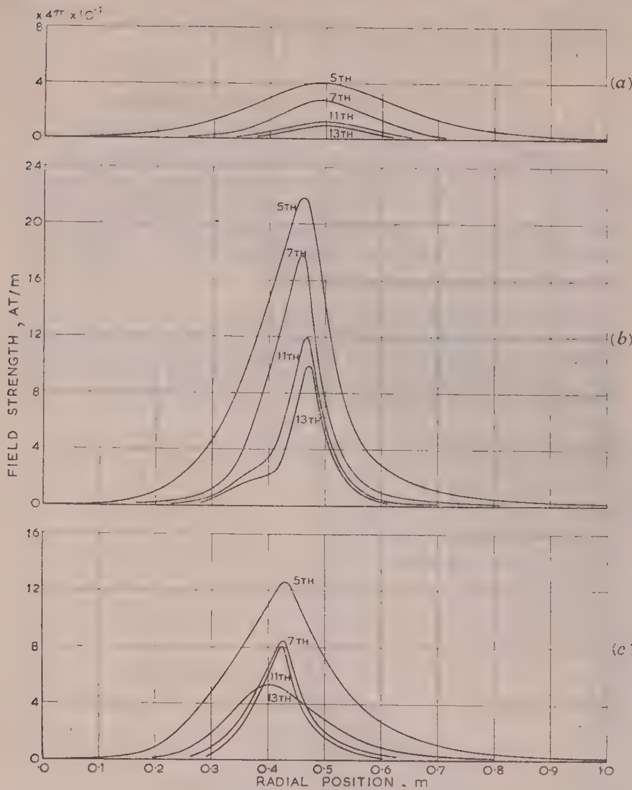

Fig. 9.—Harmonic components of field on a permeable end-plate.

(*a*) Axial.
(*b*) Tangential.
(*c*) Radial.

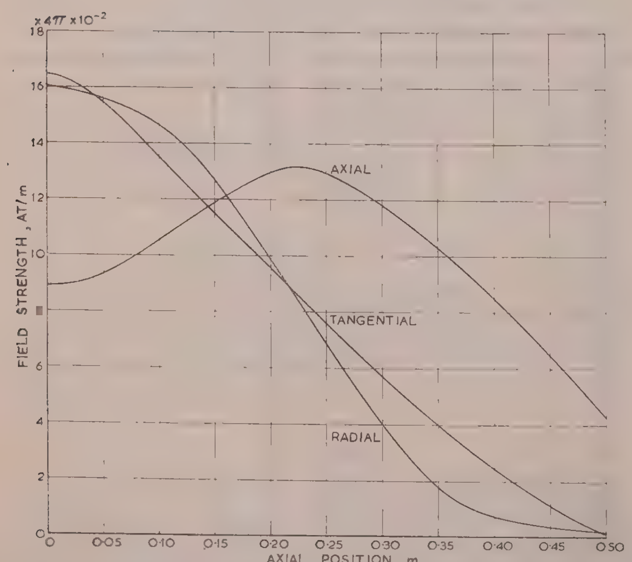

Fig. 10.—Fundamental components of field on the retaining-ring: permeable end-plate.

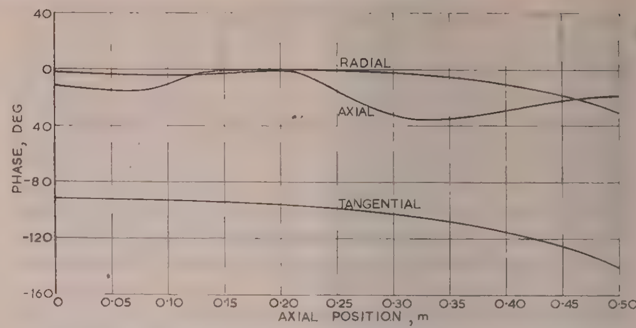

Fig. 11.—Phase of fundamental components on the retaining ring: permeable end-plate.

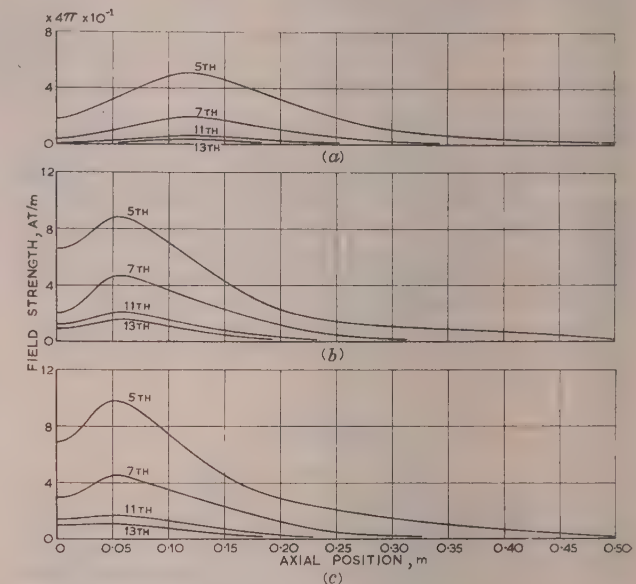

Fig. 12.—Harmonic components of field on the retaining ring: permeable end-plate.

(*a*) Axial.
(*b*) Tangential.
(*c*) Radial.

completes the change of π radians, from its original value, at the position of the minimum.

(*b*) The radial component of the fundamental wave is almost everywhere of much greater magnitude than the axial component. It has a high value at the machine axis, a maximum at the radius of the slots and it decays rapidly behind the winding to the outer edge of the end-plate. Its phase is almost constant at all positions.

(*c*) The tangential component of the fundamental wave has, at the machine axis, the same magnitude, but a phase difference of $\pi/2$ radians, as compared with the radial component. It has peaks at the radii of the two layers of the winding and decreases, in a very similar manner to the radial component, over the end-plate. Between the peaks it has a minimum, and its phase changes quickly through π radians.

(*d*) The harmonic waves of all three components have the same general distributions, decaying rapidly to zero on either side of peaks at the position of the winding. At any radius, the magnitudes of the harmonics decrease, apart from one exception [see Fig. 9(*c*)], with their order.

The main characteristics of the distribution on the rotor retaining ring are detailed below:

(i) The axial fundamental wave has a maximum midway between the ends of the retaining ring.

(ii) The radial and tangential components of the fundamental wave have very similar characteristics so far as magnitude is concerned: both decrease steadily along the ring from maxima at the surface of the end-plate and their phases differ by $\pi/2$ radians at almost all points.

(iii) All the harmonic components of the field have maxima just beyond the straight projection of the winding and they decay steadily towards the outer end of the retaining ring. The magnitudes of the harmonics decrease with increasing order. As percentages of the maximum values of the corresponding fundamentals, the 5th harmonics have maxima of about 6%.

(4.3) Influence of End-Plate Permeability

Fig. 13 shows the distribution of the fundamental waves over a surface parallel to, but 0·06 m from, the infinitely permeable

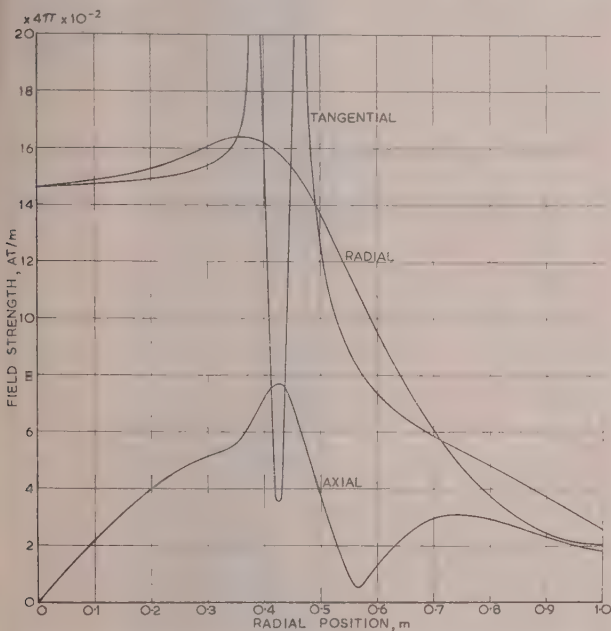

Fig. 13.—Fundamental components of field on a non-magnetic end-plate.

surface. This distribution may be interpreted as that occurring (in the absence of eddy-currents) at the surface of a non-magnetic end-plate, 0·06 m thick, placed against a highly permeable core. Most significant, as compared with the above results for a permeable end-plate, is the considerable overall reduction in the axial component. At the outside of the end-plate the radial and tangential components are reduced, although nearer the slots they are increased. The harmonic components, and the fields at the rotor surface, are almost identical with those shown above.

For the case $\mu = 0$, corresponding to complete eddy-current screening of the end-plate, all axial components of field at the end-plate surface are eliminated. In the radial field there is a large peak at the position of the slots together with a considerable increase over most of the end-plate. The tangential field is slightly reduced towards the outside of the end-plate. Curves of the field at the end-plate are plotted in Fig. 14. The harmonics at the rotor surface are again very similar to those shown in Fig. 9 for $\mu = \infty$.

(4.4) Influence of Coil Design

Three features of coil design—pitch, straight projection and cone angle—have been examined for the cases $\mu = 0$ and ∞. Coil pitch has been varied from 140° to 180°: of the fundamental

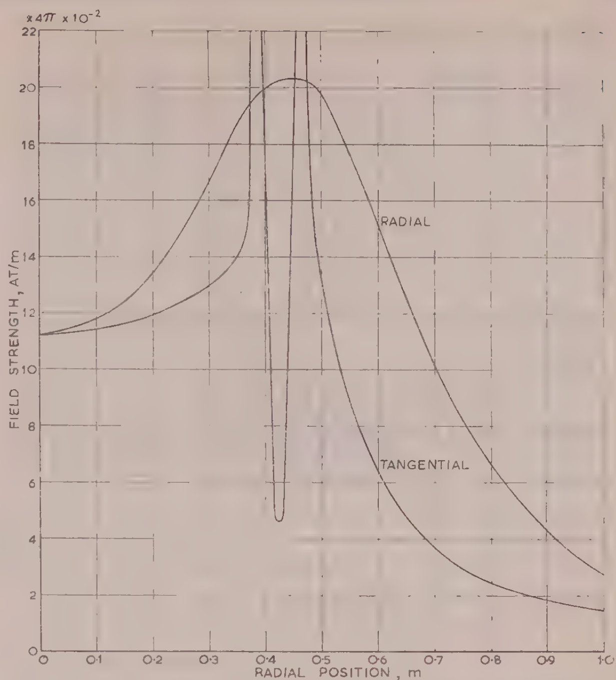

Fig. 14.—Fundamental components of field on a screened end-plate.

waves, the radial component varies negligibly and the tangential component decreases by about 8%, with reduction of pitch angle; the variation in harmonic components at the intersection of the end-plate and the retaining ring, for the case $\mu = 0$, are plotted in Fig. 15.

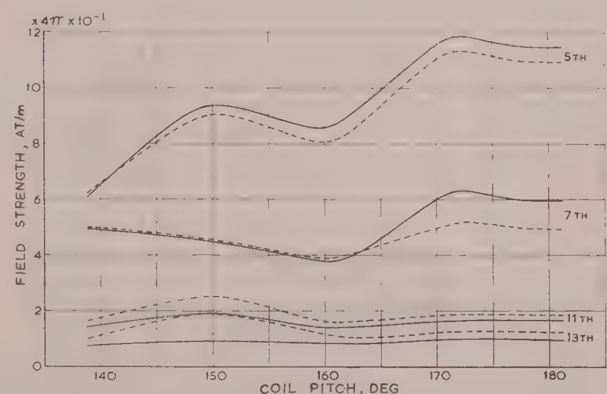

Fig. 15.—Harmonic components of field at the end-plate/rotor intersection: screened end-plate.

– – – – Tangential.
———— Radial.

In addition to the value of 0·12 m used above, straight projections of 0·20 and 0·28 m have been considered. As the projection increases with $\mu = 0$ or ∞, all components of field at the end-plate surface decrease, though the changes in tangential components are negligible. The effect on the fundamental of the axial field, with $\mu = \infty$, is shown in Fig. 16, and on the radial field, with $\mu = 0$, in Fig. 17. The harmonics at the rotor surface have the same maxima, but the length of the region over which they have these values increases so as to be always that of the straight projection.

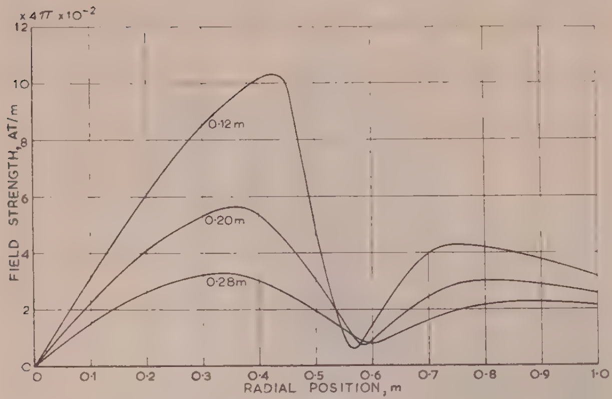

Fig. 16.—Effect of straight projection: axial fundamental on a permeable end-plate.

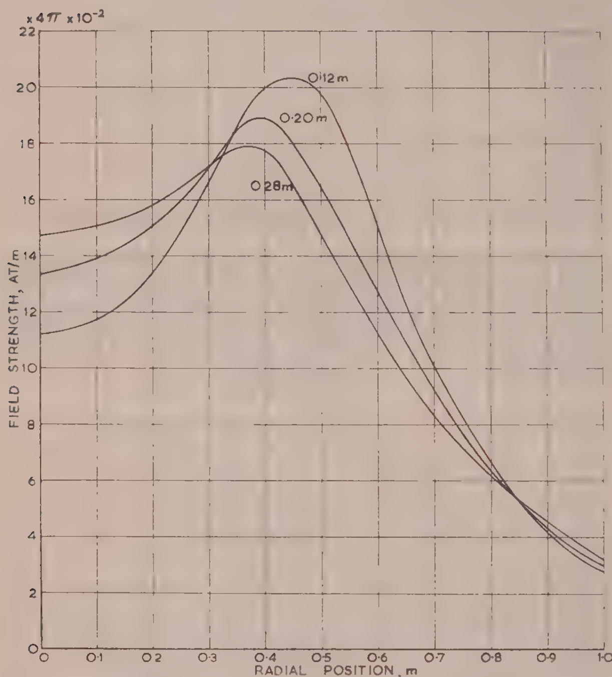

Fig. 17.—Effect of straight projection: radial fundamental on a screened end-plate.

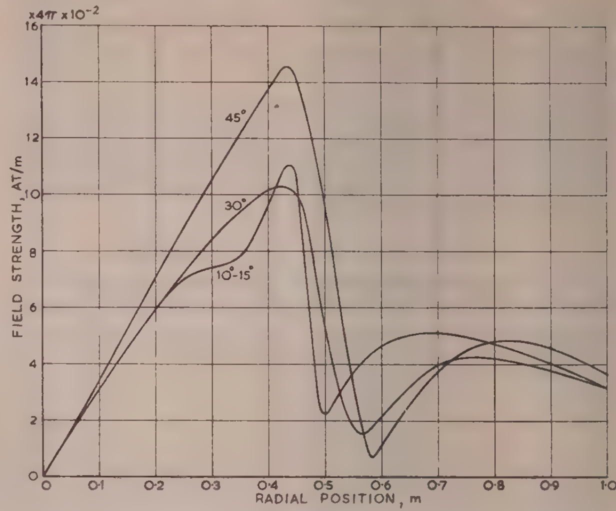

Fig. 18.—Effect of cone-angle: axial fundamental on a permeable end-plate.

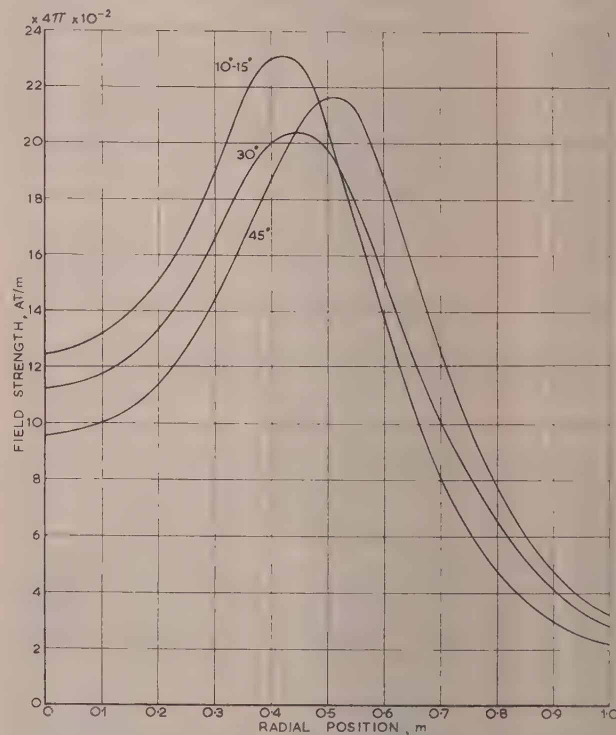

Fig. 19.—Effect of cone-angle: radial fundamental on a screened end-plate.

With the normal straight projection the effect of changing the cone angle has been examined. Two windings were used, one with a cone angle of 45°, and one in which the angle for the lower layer of the winding was 10° and that for the upper layer 15°. (This latter type of winding is used to minimize the increase in overall projection which occurs when small cone angles are used.) When $\mu = \infty$, it is found that, at the end-plate, the axial component of field immediately behind the winding decreases with decreasing cone angle but that the radial and tangential components are virtually unchanged. When $\mu = 0$, the radial and tangential components both decrease with decreasing cone angle. The distributions of the fundamental components at the end-plate are shown, for the axial field with $\mu = \infty$, in Fig. 18, and for the radial field, with $\mu = 0$, in Fig. 19. It will be noted that the magnitude of the peaks of these curves for the winding with two cone angles is out of character with those of the windings having a single cone angle. The harmonics at the rotor surface with $\mu = 0$ and ∞ increase, on the average by about 20%, as the cone angle is reduced from 45° to 10°–15°.

(4.5) Influence of Air-Gap

As pointed out in Section 3.5, the air-gap has no effect upon the end field when $\mu = 0$, but when $\mu = \infty$ the effect is considerable. The radial and tangential components of field on

the end-surface disappear leaving only the axial components. The distribution of the axial fundamental wave, due to the winding with the normal straight projection and cone angle, is shown in Fig. 20 together with that for the same conditions

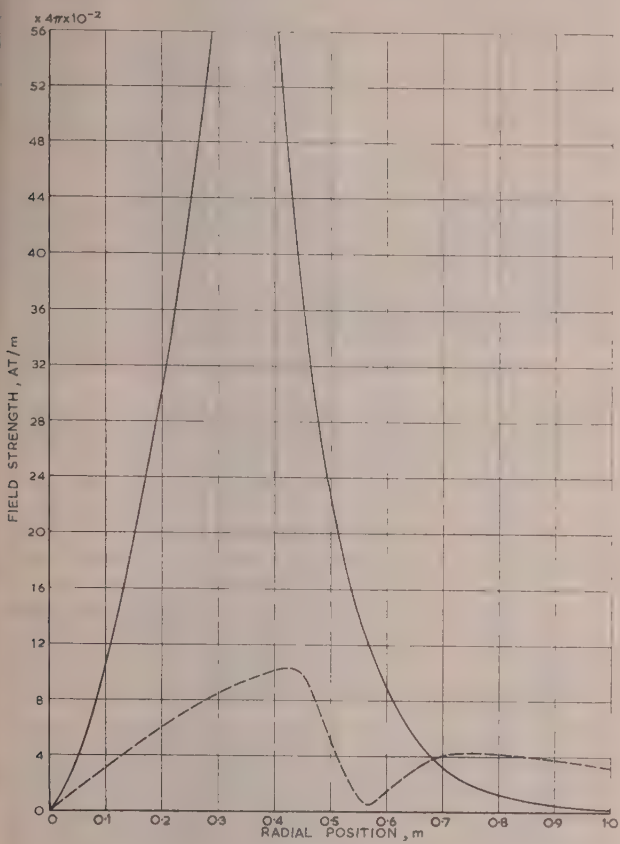

Fig. 20.—Effect of the air-gap: axial fundamental on a permeable end-plate.

———— With gap.
— — — — No gap.

though without the gap. It will be noted that the effect of the gap is to increase the axial field many times over much of the end-surface. Results for the field strength near the air-gap are unreliable and are not presented. However, it is certain that reliable results (if available) would continue the curve to much higher values than those plotted. The phase of the field reverses, of course, at the radius of the fictitious conductor.

At the retaining-ring surface the axial and radial harmonics are high, of the same order as those of the corresponding fundamental components in the absence of the gap (Fig. 10). The maximum of the axial component occurs at the end-surface and that of the radial component very close to it. The tangential harmonics are negligibly changed as compared with those for the case neglecting the gap (Fig. 12).

(5) DISCUSSION AND CONCLUSION

(5.1) General Considerations

In the paper a simple method is described by which the magnetic field of a current in a circuit of any shape can be accurately computed. It is used in conjunction with the method of images and with a fictitious air-gap conductor to examine the field distribution over the end-plate and retaining ring of a turbo-generator. Two approaches to the resultant field (and the consequent determination of eddy currents) are described: in the first, the permeability of the end-plate is taken to be infinite and the field is determined assuming initially that the modifying effect of eddy-currents is negligible; in the second, the permeability of the end-plate is taken to be zero, and the field calculated is the resultant of that applied and that due to the action of eddy currents, the magnitude of which is sufficient to prevent any flux penetration into the end-plate. Because the end of the rotor always represents a permeable boundary of the field and because the screening effect of eddy currents in the stator end is far from complete, it is the opinion of the author that the first of these approaches is the more reliable.

The method of preparing results is completely numerical, but much qualitative knowledge of the field distribution can be derived from examinations of the simple equivalent circuits to which the fields are due. (This point is elaborated below.) Two distinct components of the field can be distinguished. The first is due to the end-windings themselves, and the second, and predominant one in the case when $\mu = \infty$, is the fringe field due to the magnetization of the rotor and stator.

(5.2) Field Components

(5.2.1) Axial Components.

The fundamental and harmonic waves of the axial component of field are due to the involute parts of the winding and to the fictitious air-gap conductor. They are uninfluenced by the currents in the axial direction. On the end-plate the air-gap conductor develops only axial components.

So far as an end-plate of infinite permeability is concerned, the axial components of field are the loss-producing ones, and they have maxima at or near the position of the teeth. They induce eddy currents which flow in radial planes of the end-plate and its teeth. Their influence should be reduced by dividing the eddy-current paths—by segmenting, splitting or grooving the end-plate and splitting the teeth—and by the use of non-magnetic materials and eddy-current screens, provided that these are of sufficiently high conductivity. It should also be possible to screen the end-plate by the use of suitably laminated 'flux diverters' made of magnetic material.

(5.2.2) Tangential and Radial Components.

The tangential and radial components are generated by all parts of the winding (except that the air-gap current does not contribute to them on the end-plate). Over the end-plate they are considerably larger than the axial components due to the winding alone, and they have their maxima at or near the position of the teeth. In the case $\mu = 0$, they are associated with eddy currents flowing in axial and peripheral surfaces in the end-plate. Eddy currents due to the penetration of radial components of field into the plate and teeth should be reduced by splitting the teeth and segmenting or grooving the plate; those due to the tangential components should be reduced by peripheral grooving of the plate.

(5.2.3) Harmonic Components.

The harmonic waves of flux are chiefly significant at the retaining-ring surface, where they induce losses which may be important in connection with rotor heating problems. Their presence is due to the fact that the field is generated by discrete conductors, and the magnitude of the harmonics, therefore, increases near the windings. It also increases very much near the air-gap.

(5.3) Boundary Effects

(5.3.1) Eddy-Current Screening.

Whilst achieving the desired result of reducing the axial components of field, eddy-current screening of the end-plate has the disadvantage of increasing the radial components particularly at and just behind the teeth. Consequently, losses occurring in stationary conducting parts, including the winding, due to these components must be increased. This may account to some extent for the difficulty that seems to occur in practice in evaluating the benefits of eddy-current screening.

(5.3.2) Non-Magnetic End-Plate.

Whilst the radial and tangential components of field are not significantly changed, the axial components at the end-plate surface are much reduced by using a non-magnetic end-plate. The results presented in Fig. 13 ignore the presence of the gap, but it is apparent from a consideration of the appropriate circuit that the axial component, including the influence of the gap, would also be reduced as compared with its value, shown in Fig. 20, for the surface with $\mu = \infty$.

(5.3.3) Air-Gap.

The influence of the air-gap on the field at the surface of a permeable end-plate is very considerable. The axial component of field is many times greater than that of the field of the winding itself, and must be regarded as the chief cause of loss and heating in the teeth and the region just behind the teeth. For a given air-gap length it increases in direct proportion to the electrical loading of the stator. Note should be taken of the fact that the results presented assume a smooth end surface without slots; the presence of slots, whilst reducing the permeance of the fringe-field paths, leads to concentration of flux on the teeth where densities higher than those plotted are likely. The air-gap effect also leads to large harmonic components on the surface of the retaining ring.

(5.4) Coil Design

With regard to the influence of coil pitch, the results do not reveal any particular pattern of variation of the fundamental or harmonic field components. The coil pitch is, anyway, determined by the required air-gap waveform of the machine.

The axial component of field with $\mu = \infty$ and the radial and tangential components with $\mu = 0$ are reduced, particularly just behind the slots, both by increasing the straight projection and by reducing the cone angle of the winding. (This is to be expected since both changes increase the distance between the end-plate and the involute portion, as a whole, of the winding.) Unfortunately, both of these changes lead to a longer machine: also both, but especially the former, have the disadvantage of increasing the harmonic fields at the retaining ring.

(5.5) Field of the Rotor

The field of the rotor winding can be determined using the methods described in the paper. It can contain any odd harmonic, and these, unlike the stator field harmonics, induce currents of harmonic frequencies in the stationary parts of the end-structure. The important matter of the influence of power factor can be examined by addition of the rotor and stator fields.

(6) ACKNOWLEDGMENTS

The author wishes to thank Sir Willis Jackson, Director of Research and Education, A.E.I. (Manchester) Ltd., for permission to publish the paper. Thanks are also due to Mr. S. Neville for helpful discussion, and to Mrs. A. Griffiths for the preparation of the diagrams.

(7) REFERENCES

(1) 'Frontal Leakage Field and Additional Losses in the Ends of Turbo-Generators', *Bulletin Oerlikon*, Nos. 79 and 80, January and February, 1928.

(2) KUYSER, J. A.: 'Recent Developments in Turbo-Generators', *Journal I.E.E.*, 1929, **67**, p. 1081.

(3) KOHLER, G.: 'Über Stirnstreufelder und Zusatzverluste in Turbogeneratoren', *Siemens-Zeitschrift*, 1926, **6**, p. 605.

(4) RICHARDSON, P.: 'Stray Losses in Synchronous Electrical Machinery', *Journal I.E.E.*, 1945, **92**, Part II, p. 291.

(5) STAATS, G. W.: 'Eddy Currents in the End Portion of Turbine-Generator Stator Windings', *Transactions of the American I.E.E.*, 1957, **76**, Part III, p. 384.

(6) WINCHESTER, R. L.: 'Stray Losses in the Armature End Iron of Large Turbine Generators', *ibid.*, 1955, **74**, Part III, p. 381.

(7) HARRINGTON, D.: 'Forces in Machine End-Windings', *ibid.*, 1952, **71**, Part III, p. 849.

(8) MAYER, D.: 'Mechanické síly působící na čela vinutí statoru střídavých strojů', *Elektrotechnicky Obzor*, 1955, **44**, p. 395.

(9) YOUNG, J. B., and TOMPSETT, D. H.: 'Short-Circuit Forces on Turbo-Alternator End-Windings', *Proceedings I.E.E.*, Paper No. 1683 S, July, 1954 (**102 A**, p. 101).

(10) CARPENTER, C. J.: 'The Application of the Method of Images to Machine End-Winding Fields', *ibid.*, Paper No. 3327 U, October, 1960 (**107 A**, p. 487).

(11) HAMMOND, P.: 'Electric and Magnetic Images', *ibid.*, Monograph No. 379, May, 1960 (**107 C**, p. 306).

(12) DOUGLAS, J. F. H.: 'Reactance of End-Connections', *Transactions of the American I.E.E.*, 1937, **56**, p. 257.

(13) HALACSY, A. A.: 'Practical Calculation of Magnetizing Force', *Proceedings I.E.E.*, Paper No. 957, March, 1950 (**97**, Part I, p. 37).

(14) HALACSY, A. A.: 'Calculation of Magnetizing Force', *Transactions of the American I.E.E.*, 1952, **71**, Part I, p. 90.

(15) SEARLE, G. F. C.: 'On the Magnetic Field due to a Current in a Wire placed Parallel to the Axis of a Cylinder of Iron', *The Electrician*, January and February, 1898, **41**, p. 543.

(8) APPENDIX

(8.1) Magnetic Field of a Straight Current Filament

Referring to Fig. 1, the magnetic field of the filament AB at F has a magnitude, given by eqn. (1), of

$$H = \frac{1}{4\pi}\frac{i}{\mathrm{FP}}(\sin\theta_{n-1} - \sin\theta_n)$$

with the direction of the normal to the plane ABF. The expression for magnitude may be written

$$H = \frac{1}{4\pi}\frac{i}{\mathrm{FP}}\left(\frac{\mathrm{AP}+\mathrm{AB}}{\mathrm{FB}} - \frac{\mathrm{AP}}{\mathrm{AF}}\right) \quad . \quad . \quad . \quad (4)$$

where FP is given by

$$\mathrm{FP} = \sqrt{(\mathrm{AF}^2 - \mathrm{AP}^2)} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

All lengths may be expressed in terms of the co-ordinates as follows: forming

$$a_x = x_n - x_{n+1} \quad b_x = X - x_n \quad c_x = x_{n+1} - X$$

$$a_y = y_n - y_{n+1} \quad b_y = Y - y_n \quad c_y = y_{n+1} - Y$$

and $\quad a_z = z_n - z_{n+1} \quad b_z = Z - z_n \quad c_z = z_{n+1} - Z$

gives
$$AB = \sqrt{(a_x^2 + a_y^2 + a_z^2)} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$AF = \sqrt{(b_x^2 + b_y^2 + b_z^2)} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and
$$FB = \sqrt{(c_x^2 + c_y^2 + c_z^2)} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Also, since the direction cosines of AB, l, m and n, are

$$l = \frac{a_x}{AB} \qquad m = \frac{a_y}{AB} \qquad n = \frac{a_z}{AB}$$

AP is given by

$$AP = lb_x + mb_y + nb_z \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The sign of AP is positive or negative according as P is on the opposite or the same side of A as is B. Substitution from eqns. (5)–(9) into eqn. (1) gives the field strength in terms of the co-ordinates.

To determine the direction cosines of the normal to the plane ABF, the equation of the plane must first be determined. Let this equation be

$$px + qy + rz + s = 0 \quad . \quad . \quad . \quad . \quad . \quad (10)$$

then, since three points on the plane are known, we may write

$$px_n + qy_n + rz_n + s = 0 \quad . \quad . \quad . \quad . \quad (11)$$

$$px_{n+1} + qy_{n+1} + rz_{n+1} + s = 0 \quad . \quad . \quad (12)$$

and
$$pX + qY + rZ + s = 0 \quad . \quad . \quad . \quad . \quad (13)$$

Elimination of p, q, r and s from the eqns. (10)–(13) gives the equation of the plane as

$$\begin{vmatrix} x & y & z & 1 \\ x_n & y_n & z_n & 1 \\ x_{n+1} & y_{n+1} & z_{n+1} & 1 \\ X & Y & Z & 1 \end{vmatrix} = 0$$

The direction cosines of the normal to the plane are of the form

$$L = \frac{p}{\sqrt{(p^2 + q^2 + n^2)}} \qquad M = \frac{q}{\sqrt{(p^2 + q^2 + n^2)}}$$

$$N = \frac{r}{\sqrt{(p^2 + q^2 + n^2)}}$$

so that, by comparison with the expanded form of the determinant, the direction cosines of the normal to ABF are

$$L = \frac{a_z c_y - a_y c_z}{K}$$

$$M = \frac{a_x c_z - a_z c_x}{K}$$

and
$$N = \frac{a_y c_x - a_x c_y}{K}$$

where
$$K = \sqrt{[(a_z c_y - a_y c_z)^2 + (a_x c_z - a_z c_x)^2 + (a_y c_x - a_x c_y)^2]}$$

Thus, resolving the field into components parallel to the x-, y- and z-axes gives

$$H_x = LH \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

$$H_y = MH \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$H_z = NH \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

DISCUSSION ON THE ABOVE TWO PAPERS BEFORE THE SUPPLY SECTION, 12TH APRIL, 1961

Mr. V. J. Vickers: The papers make a very valuable contribution on a subject which has been seriously neglected. The reasons for this neglect can be attributed to the complexity of the problem and the lack, hitherto, of tools for carrying out the necessary analyses. With the advent of computers and computer techniques, we are now at last at the stage where analytical results are beginning to be of assistance to designers.

I hope that the authors have only paused at the stage of investigating the fields and that we may see further work done leading to a more practical application to the estimation of the resulting losses.

I was disappointed that the first paper made virtually no reference to the material of the rotor retaining ring, and that Mr. Lawrenson in his paper only points out that, provided that it is non-magnetic, as is usual, it can be neglected. Because of the problems in the manufacture of these large rings with high mechanical properties, one is often tempted to change over to rings of magnetic material. The effect of such a change of material upon the stray load loss can be very significant; in an extreme case the value of the stray load loss has been nearly doubled. Attention to details in the end-winding structure and adjacent parts can reduce the difference, but even so, it remains significant particularly with the large very highly rated machines. Can the authors adapt their respective analyses to take account of the permeability of the end-bell material? If they can, as there is a large amount of experimental data available on duplicate machines, some having magnetic and some having non-magnetic retaining rings, it should be possible to correlate, to some extent, the field and the loss resulting from it, which, after all, is the basic problem in which we are all interested.

Mr. Lawrenson dismisses the shaft as being relatively unimportant because it is small and at a distance from the stator winding. I would question this assumption particularly because most constructions employ a relatively heavy disc of magnetic material to support the outer end of the end bell, and it is known from experimental results that quite strong fields do in fact exist in this region. Can the authors say whether their methods can be modified to take account of this boundary?

In view of the increasing interest in stray load losses of induction motors in which a concentric winding, also known as a hair-pin winding, is commonly used, can the authors say if their respective methods can be modified to estimate the field of a winding of this type, or does the general lack of symmetry compared with the basket winding make the analysis far too cumbersome?

Mr. F. R. L. Creek: As a designer of turbo-generators, I am primarily interested in the results and the conclusions drawn, particularly in so far as they affect the stray losses in the end structure and end-windings. To some extent I disagree with Mr. Lawrenson in his conclusions as to the effectiveness of flux shields over the stator end-plate.

The majority of turbo-generators made in recent years by my company have flat non-magnetic cast-iron end-plates with integrally cast fingers for tooth support. These end-plates were difficult to screen effectively, except on the rear surface, and several highly rated machines have since been built with non-magnetic steel tooth supports and separate steel backing plates. The steel backing plates were screened on the end-plate surfaces by heavy copper shields which were wrapped round between the inner edge of the end-plate and the winding.

Although test results showed that there was an appreciable loss in the screen and the overall loss was apparently not much

reduced, the maximum end-plate temperatures for comparable loading and cooling conditions were only about one-third of those experienced on the earlier designs.

On one of these machines with a water-cooled stator winding it was possible to separate out the stray eddy losses in the stator end-winding by calorimetry, and these were found to be a relatively small part of the total stray load losses.

Although Mr. Lawrenson's proposal for a laminated flux diverter across the end-plate is, at first sight, attractive, I suspect it would in fact shorten the leakage path and as a result increase the leakage flux with a possible increase in loss in the stator end-windings.

Harmonic fields at the retaining-ring surface may well be important; further work by the authors on this subject would be welcomed, as it is particularly difficult to assess experimentally the magnitude of stray losses due to this cause.

Mr. C. J. Carpenter: In both papers a bold attack has been made on the end-field problem and very considerable trouble has been taken to allow accurately for the shape of the end-windings, so that the calculations should be capable of providing accurate estimates of the field in the vicinity of the conductors. It would thus appear that a very satisfactory basis has been provided for the estimation of short-circuit forces and of end-winding reactance, both of which depend primarily on the winding geometry, and I am surprised that in neither paper is there more explicit reference to these two problems. On the other hand, the magnetic effect of the iron is ignored by Messrs. Ashworth and Hammond and is allowed for in terms of only a very simple approximation by Mr. Lawrenson. It thus seems inappropriate that, in both papers, the field components have been calculated on a plane corresponding to the core end surface, i.e. where the method of calculation is least applicable, and that conclusions have been drawn concerning the end-plate losses. Surely, for the purpose of loss calculations, the exact shape of the end-winding conductors is of much less importance than the boundary conditions imposed by the plate in which the loss occurs?

There is no obvious justification for relating the losses in a piece of iron to the field which would be present if the iron were not, as is done in Section 7 of the first paper. Similarly, in the second paper, most of the results are calculated on the assumption that there is no air-gap, and this leads to the prediction of tangential and radial field components which are wholly fictitious if the iron is, in fact, infinitely permeable. As Mr. Lawrenson suggests in Section 1 'the loss in a region is proportional (in some way) to the magnitude of the appropriate components of the field there', but are these components those given in the paper? There need not be any relationship between the losses and the field components present when the boundary conditions are changed. What is the justification for the remark in Section 5.2.1 that it is the axial component of the field which produces the losses, bearing in mind that the skin-effect phenomenon depends on the tangential component?

It is possible to make a relatively simple calculation of the end field by ignoring the curvature of the windings, and this is sufficient, for example, to establish the same general conclusions as those drawn in the paper about the effect of cone angle and of the length of the straight projection. The loss problem may perhaps be better analysed in this way so that analytical rather than numerical results are possible and the effect of loss-reducing devices can therefore more easily be assessed.

Mr. V. Easton: Referring to Fig. 17 of the first paper, could the authors add the values corresponding to steady short-circuit? This condition is the present basis for measuring the stray loss for conventional efficient calculations, and it would be interesting to know where the points lie in relation to the curves for a loaded machine. On the basis of actual temperature rise experience indicates it corresponds approximately to unity power factor. The conclusion, from this Figure and the known shape of the actual temperature-rise/power-factor curves, that the axial component of flux is relatively unimportant is at variance with the second paper and is not what would be expected. There is also some discrepancy between Fig. 7 and the statement in Section 5.3 that the maximum of H_r occurs at larger radii as the cone angle is increased.

Fig. 18 of the second paper neglects the effect of the air-gap and therefore could give an incorrect picture of the effect of the cone angle. Mention is also made of the material of the coil retaining rings, and it has been suggested that the use of magnetic steel will materially increase the field strength and stray loss. If the comparison is made on generators designed many years ago the effect is appreciable but with some modern methods of construction the increase in loss is not large. Comparative tests made some years ago on a relatively easily rated hydrogen-cooled generator gave an increase in stray loss of about 10%. Applying direct cooling to the same frame, the output was doubled, and although the overall stray loss was increased, owing to the higher stator specific loading, the effect of the magnetic retaining rings was reduced to the order of 5%. This is acceptable to permit use of assured and reliable material.

Could Messrs. Ashworth and Hammond define more clearly the meaning of H_r, H_θ and H_z? Mr. Lawrenson should clarify the scales of the fundamental and harmonic components; it would appear that, to plot on the same basis, the vertical scale of the latter should be multiplied by 10 giving harmonic components much larger than the fundamental.

Mr. A. Hunt: The authors' simplifications, ignoring the iron and the air-gap, have given undue prominence to the radial and circumferential fields. As Mr. Lawrenson shows (in Fig. 20 only) the air-gap greatly increases the axial field in the tooth region. Consequently, although the curves of Fig. 17 in the first paper are valid for the conditions assumed, they cannot fairly be offered as an explanation of the end heating which occurs at leading power factors.

By making flux plots, in which the air-gap, iron surfaces and screening effects were fairly realistically represented, we have estimated the leakage fluxes at various power factors. The axial components were the most important ones, and we estimated the loss in the teeth due to them. The loss/power-factor curve is similar in shape to the temperature/power-factor curves obtained in service.

Mr. Lawrenson refers to the importance of the rotor fringe field. We recently observed, on a 200 MW alternator, a reduction of about 50 kW in open-circuit core loss as a result of slitting the stator teeth radially to an axial depth of about 6 in at each end of the core. On short-circuit, however, there was no significant reduction of loss; tooth temperatures were however reduced, presumably by improved cooling.

Mr. Lawrenson hints at methods of reducing stray losses; how effective does he consider different methods to be? Have the authors considered the losses that may be caused by connection rings behind the end-winding? In a 500 MW machine these rings may be carrying around 12 kA.

Mr. D. C. Macdonald: The two papers have calculated the field at the end-plate and the field on the surface of the rotor. Although these have considerable bearing on the losses associated with the ends of the machine, there are losses in the end-windings which should be considered. These fall into two distinct classes. First, there are local eddy-current losses within individual strands of the windings due to the leakage field in the end-windings. Secondly, in a Roebel bar wave winding, there are strands in parallel which have different leakage

reactances, the distribution of the current between these strands is non-uniform, and the loss throughout the length of the winding is increased.

My work has been concerned with water-wheel alternators and other salient-pole synchronous machines. On several recent machines, we have made search-coil measurements to obtain flux densities in the end regions, and also local specific loss measurements by the initial rate of rise of temperature method. These have shown, in water-wheel alternators, that the end-plate loss is small in a well-designed machine in which the salient pole is approximately the same length as the stator.

However, there is considerable loss in the end-windings due to the field produced by the currents in them. Our search-coil readings have shown that the field in the vicinity of the conductors is complicated, varying considerably over any one bar, depending on which layer the bar is in and its position in a phase band. These losses can amount to about one-fifth of the d.c. I^2R loss on some water-wheel alternators, and are probably greater on turbo-alternators. Richardson in a paper some years ago quoted a factor of 2 or 3 for the ratio of a.c. to d.c. loss in the windings of a 2-pole machine.

Are these analyses applicable to the calculation of the field in the vicinity of the windings? In Part 1 of the first paper, Mr. Hammond says that the magnetic field of a suitable arrangement of current sheets can correctly describe the magnetic field of the conductor currents except in the immediate vicinity of the conductors. It therefore appears that the current-sheet analysis is not applicable in its own vicinity. However, the current-element analysis can be made as detailed as one may choose, and it should be possible to determine the field in the vicinity of the windings.

Mr. P. Richardson: The heating of stator core ends at unity and leading power factors was observed in the United States some years ago, and a number of characteristic heating curves showing the variation in temperature with power factor at constant apparent power were published. The explanation of this effect put forward at that time seemed to be associated with magnetic saturation of the rotor retaining ring, and since variation in heating was observed to a lesser degree with non-magnetic retaining rings, it seemed that the theory was not complete.

A few years ago, I put forward the theory* that core end heating was caused by an end leakage field having two components, one depending on the stator m.m.f. and the other on the air-gap flux required to produce the machine voltage. This theory was consistent with our observations that the temperature rise of a stator core end, under a sustained 3-phase short-circuit condition, was appreciably more than with the same current at zero power factor with voltage conditions established. It is gratifying to find that the authors have developed a similar theory confirming my own views.

Much work has been done on flux mapping which has proved a useful tool. Have the authors made a comparison between results obtained from flux mapping and those of their calculations?

Section 5.4 of the first paper is misleading since it states that the field varied dominantly as sin μ, and also that the field is independent of chording angle. These do not seem consistent. Why is it stated in Section 5.5 that the straight projection of the winding must be longer for lower values of cone angle in order to maintain insulation clearances?

Was the scale model of the winding supported in a non-magnetic frame to avoid the inaccuracies which would have been introduced by an iron structure? The flux field around the model end-winding would contain harmonics interfering with the accuracy of measurement. Were these filtered out?

The calculations, applied to a coil pitch between 140 and 180°, should be continued down to 120° as this type of winding has been used so extensively in the United States.

In Section 7, in connection with Fig. 16(*a*), it is stated that the radial field must be constant at the air-gap radius. From Fig. 16(*a*) it is seen that this point is at $r/\rho = 0{\cdot}8$, but in Section 5.1 the air-gap is stated to be at $r/\rho = 0{\cdot}75$. Is there a reason for this discrepancy?

Mr. D. G. Taylor: The two papers are based on quite different methods for representing the stator windings. In the first paper the use of tubes and discs leads to analytical solutions. There is some advantage in this since some features of the results are apparent from the form of the expressions. However, the more subtle features are appreciated only when the expressions are evaluated for particular cases. I think that the advantages of obtaining analytical solutions will diminish as the complexity of the studies increases. The filament method used in the second paper has the advantages of simplicity and of representing accurately the configuration of the machine coils.

The results of the second paper show the importance of considering the air-gap and the boundary formed by the core end-plate. Probably further refinements will be needed if, as Mr. Lawrenson suggests, his method is applied to the determination of forces on the end-windings. In this problem (Reference 9) the radial components of flux density in the region between the core end-plate and the coil knuckles are of great importance, and as shown in Section 4.5 the method as it stands is not reliable here.

Both papers describe work which is progressing, and an important feature of the techniques used is their flexibility in permitting further refinements to be introduced as the studies become more complex. Complications in the form of increased arithmetic are probably not important in view of the rapid development of high-speed digital computers. Would the authors comment on the more fundamental complexities which refinements to boundary shapes will introduce in their respective methods?

Mr. K. C. Parton: Comparing the two papers, there is, with the large, fast computers now available, some tendency to prefer the methods used by Mr. Lawrenson. This is possibly dangerous in that it may be done to the detriment of the analytical approach adopted in the first paper. While it is agreed that the sledge-hammer method of the second paper is very good for getting down to details, it has to be remembered that even on a large computer, if you want to incorporate such a calculation into a full programme for machine design, it may still prove to be too time consuming. Continued work on the analytical side, however, can often lead eventually to more elegant and efficient results in mathematical form.

I was surprised that, in the Preface, the second paper is referred to as being more accurate than the first: the curve in Fig. 18 of the first paper comparing test results with calculations is very accurate. Presumably, for greater accuracy the authors could have taken two current sheets for the 'go' and 'return' paths and an extra radial disc for the nose of the winding.

Referring to the method used by Mr. Lawrenson, calculated results, in the absence of iron, comparable with the figures of the first paper, would have been appreciated.

The image principle, as it stands, is only correct for coils facing an infinite iron surface. In the case of the end-winding region, however, the winding and core are of comparable size. Could the author comment on how this is likely to affect the accuracy of the results?

Test results showing the calculated fields using different permeabilities and comparing them with actual test results would

* Richardson, P.: 'Design and Application of Large Solid-Rotor Asynchronous Generators', *Proceedings I.E.E.*, Paper No. 2492 S, January, 1958 (105A, p. 332).

have been very instructive and are a disappointing omission from the paper.

Mr. A. B. J. Reece: In the first paper, the authors mention briefly the work of Smith and Honsinger, in which boundary conditions were considered. Although the papers referred to contain a number of imperfections, the methods used, which are based on the concept of scalar magnetic potential, can lead to very useful results. The results are unlikely to prove more difficult to interpret than those which the authors will obtain when iron boundaries are taken into account.

In Section 5, an explanation is offered for the fact that, for a given electric loading, the leakage field values of a 2-pole machine are found to be larger than those of a 4-pole machine. Although the explanation is valid for coils entirely in air, a rather different consideration arises in the practical case where there are permeable boundaries. Much of the flux path is then in iron, and the most significant reason for the larger field of the 2-pole machine is the greater m.m.f. per pole acting between the iron surfaces.

Mr. Lawrenson has treated the coil shape very accurately. Unfortunately, his assumptions with regard to boundary conditions, although understandable from the point of view of ease of analysis, are only partly justified by the arguments of Section 3.2. For example, analogue studies show that the rotor shaft and magnetic components mounted on it can have a considerable influence on the end-zone flux distribution. The effect of these components is likely to be particularly important when considering end-winding eddy-current losses, inductance and forces.

The assumption of a single boundary condition on the plane of the rotor-stator end surface is an essential part of any analytical approach. In practice, however, conditions differ greatly between the slotted portion of the stator end surface, where the limited dimensions prohibit appreciable screening, and the region of the end-plate body, where screening may be nearly complete. For this reason, preliminary studies of, for example, the effect of end-plate permeability or the addition of a screen, are best made on an analogue of the end space. 'Mixed' boundary conditions and complex boundary shapes can readily be simulated on an analogue, and analogue studies can therefore form a useful complement to purely theoretical treatments. Ultimately, of course, calculated results should be checked against measurements made on a model and/or production machines.

Monsieur G. Darrieus (*France: communicated*): The first paper, which completely neglects the influence of the iron, cannot hope to furnish a solution of the end fields which is even roughly acceptable. The second is certainly nearer the truth, in that it takes into consideration the end surface of the iron, but the neglect of the cylindrical surface of the core hardly leads one to expect a satisfactory agreement with reality. The hypothesis which it adopts of an infinite permeability is reasonable, but it necessarily requires the existence of an air-gap and open slots, for which results the case of Fig. 5 (*b*) does not appear to have any physical significance.

Contrary to popular opinion, the complete field of the end-windings can be determined with as much accuracy as desired by Lehmann's method, which can be conveniently adapted to the present case of a system of revolution with sinusoidal distribution of quantities round the axis.

The graphical method is the only one which, up to now, has been shown to be capable of allowing for the conditions, within practical limits, which are determined by the shape and materials of the end-plates, end casings, etc., without neglect of anything which its application and experimental confirmation show to be important.

Although its application may be somewhat laborious, requiring several hours for each type of field, it can readily be used with practice by anyone familiar with the laws of electromagnetism (Maxwell's equations) and having a flair for design; the use of analogue methods, such as the electrolytic tank, which has been proposed but not, as far as I know, been sufficiently developed for this problem, should also be of assistance.

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSION

Messrs. D. S. Ashworth and **P. Hammond** (*in reply*): We fully agree with Mr. Vickers that the method presented in our paper needs to be extended and applied to the practical problem of stray losses. We have submitted what is in essence an interim report and we hope that Mr. Vickers and his colleagues will contribute to the solution of the outstanding problems. In particular, we feel that it should be possible to make allowance for the permeability of the end-bells in order to test whether non-magnetic end-bells are essential. As regards concentric windings, these can readily be represented by current sheets, the representation being if anything simpler than that of involute windings.

It is interesting to hear of Mr. Creek's experience with screened end-plates.

Mr. Carpenter is right in drawing attention to the difficulties presented by the complicated iron boundary. We saw these difficulties and decided to turn our back on them because we could not solve them all at once. We feel Mr. Carpenter is unduly gloomy in thinking that there is no relationship between the magnetic field of the currents in the winding and that of the iron surfaces. We are attempting to solve one problem at a time.

Mr. Easton asks for the values of the magnetic field under short-circuit conditions. These can be obtained by finding the difference between the curves in Figs. 6 and 14 after applying the relevant multiplying factors mentioned in Sections 5.1 and 6.3. H_r, H_θ and H_z are the three space components of the magnetic field H in a cylindrical system of co-ordinates, of which the machine centre-line forms the z-axis.

We appreciate Mr. Hunt's cautious reception of Fig. 17. Clearly this Figure does not give the whole story, but we think that it deserves close consideration.

Mr. Macdonald's investigations are very valuable, and it appears that the end-plate losses are smaller in multi-pole machines. The accuracy obtainable with current sheets can be increased by taking several sheets, as pointed out by Mr. Parton.

Mr. Richardson has made valuable contributions to the subjects discussed by us. We should be grateful to have references to the detailed flux mapping to which he refers. The field is independent of chording angle for a particular value of *current line density*. The question of insulation clearances depends on design practice and is not essential. The scale model was entirely non-magnetic. The air-gap extends from $r/\rho = 0\cdot71$ to $r/\rho = 0\cdot76$. The curves in Fig. 16(*a*) are thus slightly incorrect.

Mr. Taylor's question about computer difficulties has been largely answered by Mr. Parton.

Monsieur Darrieus should be assured that we do not despise graphical methods. The advent of the computer has, however, opened up the possibility of applying analytical solutions as pointed out by Mr. Vickers. Thus the designer now has a new weapon, which promises to be of considerable help.

Mr. P. J. Lawrenson (*in reply*): With regard to the limitations and flexibility of the method of analysis I would emphasize that

the technique of using current filaments permits the derivation of results which are valid in the region of the conductors, and it makes simply possible the representation of windings of any shape or type. Thus, there is no difficulty in the treatment of the connector rings of a turbo-generator or of a concentric, induction-motor winding—in fact, the latter has already been examined in an investigation of the forces experienced by such a winding. With irregular windings, of course, it is not possible to use distribution factors, as was done in the paper. The computation time involved for any problem is never likely to become unreasonably long.

Using the method of images the influence of cylindrical surfaces, such as retaining rings, shaft and outer casing, on the fields of 3-dimensional current arrays can be accounted for approximately. As a result the most general boundary that can be treated consists of two cylinders (representing the outer casing and the shaft or retaining ring) and two planes (representing the end-plate and end casing) perpendicular to the axes of the cylinders. The treatment of discs or other magnetic items mounted on the shaft is not possible. In my opinion, the best method of representing a cylindrical boundary is to form the image as the inverse of the actual circuit in the cylindrical surface. Using this representation the influence of the shaft on the field of the stator winding is not great—at all points on the retaining-ring and end-plate surfaces it results in changes in field of less than 10%. (Its effect on the field of the rotor currents is, of course, greater.) The effect of treating the end-plate as infinite is to produce values of field which on the end-plate at a radius just less than that of the plate are too low, and which towards the coil noses are rather too high. There is little effect nearer to the axis of symmetry of the field. By representing additionally the outer casing of the machine any doubts caused by treating the end-plate as infinite (Mr. Parton) or neglecting the machine core (Monsieur Darrieus) can be removed.

Knowing the present state of knowledge Mr. Hunt will not be surprised if I do not accept his invitation to classify various loss-producing methods. I would say, however, that I think splitting of the teeth (and end-plate where this is possible) is likely to reduce eddy currents. This has been the experience in America, and Mr. Hunt's results on open circuit strongly support the view. (Without full information concerning the tests I would not like to comment on the apparent failure of the splitting to reduce losses on short-circuit.) As I said in the paper, I think that laminated magnetic screens or diverters are also likely to be effective, and good reports, though few details, are to be found in the literature. However, I agree with Mr. Creek that, because they increase the permeance of some flux paths linking the winding, such screens may increase those losses occurring in the copper. Losses in the end copper are considerable, as Mr. Macdonald points out, and it may be desirable, either in conjunction with the use of screens or otherwise, to subdivide the conductors to a greater extent than is done at present. Again, as Mr. Macdonald mentions, care is also necessary in the transposition of the straps in the windings to prevent currents circulating round large sections of the complete winding.

Mr. Carpenter has raised a great many points which I shall treat in order.

(*a*) Contrary to his suggestion, it is appropriate, using the only method available at the present time, to base conclusions about the eddy-current losses upon knowledge of the field distribution over the surfaces of the bodies of interest (having allowed in the calculation of the field for the presence of the bodies).

(*b*) As Mr. Carpenter implies, adequate representation of the boundaries is most important in any consideration of losses. However, there is no question of choosing between the accuracy of winding or boundary representation. Detailed representation of the boundary, both shape and conditions, is impossible at present, but it is maintained that the simplified representation used gives a reasonable indication of conditions over much of the end-plate and retaining ring.

(*c*) It is surprising that it should be necessary to point out that, when the end-plate is infinitely permeable, the radial and tangential components of field are zero. This is clearly stated and kept in view throughout the paper.

(*d*) With regard to loss-producing components of field, assuming the end-plate to be infinitely permeable, there are only axial components of field *applied* at the surface. Movement (or alternation) of these components induces e.m.f.s in the surface, and the resulting eddy currents can be estimated to a first approximation. The eddy currents modify the applied field, but so far it has not been found possible to account exactly for this reaction even with the simplest boundary shapes. The eddy currents also *set up* a tangential field (they are not, in this case, produced by such a field, as Mr. Carpenter seems to suggest), and the calculation of this field on the assumption that eddy currents completely eliminate the applied axial field (i.e. with $\mu = 0$) could provide an alternative means of estimating the currents themselves.

(*e*) The idea that by replacing the detailed winding representation by one neglecting curvature it would be possible to produce analytical rather than numerical results is, I think, incorrect. In both treatments the basic analysis is of the influence of a single, straight element, and the total result is obtained by summation of the effects due to several elements. Whether the summation extends over a few or many elements does not change the form of the analysis.

In reply to Mr. Easton's point concerning the effect of cone angle, since the effect of the air-gap is independent of the cone angle (for the analysis given), the differences between the curves in Fig. 18 do give the differences to be expected, even allowing for the air-gap (by superposition), owing to changes in cone angle. (I think the assumption made in the analysis that the air-gap has little effect on the field of the windings which lie outside the core end is a reasonable one.)

The points raised by Messrs. Reece and Easton concerning the scale of the flux-distribution curves have arisen from a misunderstanding of the factors '$\times 4\pi \times 10^{-1}$', etc. These are meant to indicate that the values plotted are the actual values multiplied by the factor, and not that the plotted value should be multiplied by the factor to give the actual value.

In connection with the point made by Monsieur Darrieus concerning Fig. 5(*b*), the question of gap and slots is considered in Section 3.5. It would be interesting to have more details of the extension of Lehmann's method to the treatment of 3-dimensional fields.

DISCUSSION ON

'THE IMPULSE STRENGTH OF FULLY-IMPREGNATED-PAPER DIELECTRICS AS USED IN HIGH-VOLTAGE CABLES'*

NORTH-WESTERN CENTRE, AT MANCHESTER, 11TH APRIL, 1961

Mr. F. Mather: Operating experience shows that very close control of workmanship is necessary in cable manufacture if the qualities of the insulating materials are to be fully utilized.

Referring to Fig. 1, I wonder whether it is safe to judge the effect of paper density on impulse strength from nine tests with a standard deviation reaching 50 kV/cm.

Fig. 2 shows that increase in air impermeability results in some increase in impulse strength, but here again the number of tests seems rather small in view of the standard deviation, which reaches 56 kV/cm. The effect of paper thickness as shown in Fig. 4 is much more decisive.

It is stated in Section 5.3 that 'there can be little doubt that breakdown is initiated in the impregnant as distinct from the cellulose fibres'. Is it not possible that breakdown occurs at the inter-face between the impregnant and the fibres?

If impulse strength decreases with increasing temperature, should not the tests be carried out at a core temperature of 120–160° C, since, during a prolonged lightning storm, a cable may first have to carry short-circuit current and then be subjected to a surge before it has had a chance to cool?

Is the impulse strength of a cable often a limiting factor if the paper thickness is designed to withstand the long-term 50 c/s stress and switching over-voltages?

Mr. F. W. Taylor: The fact that charged globules of oil were clearly visible in samples which had been tested but not broken down seems to indicate that forces due to local ionization had driven the oil away from a region of high stress. If so, ultimate breakdown would have occurred due to lack of oil at this spot.

I agree that the impulse strength of oil-impregnated paper is primarily dependent on the impregnant, but would have thought that the impulse strength of the impregnant itself would depend to some extent at least on the processing. The oils for the model cables were processed in a vacuum of 0·2 mm Hg, and impulse strengths of around 1 000–1 400 kV/cm are given. The oils for the oil tests mentioned, however, are only processed to a final vacuum of 10 mm Hg and give very similar breakdown values at distances equivalent to the length of the butt gaps, if allowance is made for increase in stress due to the higher permittivity of the paper. Does this mean that there is no difference in impulse strength of cable oils when processed at 10 and 0·2 mm Hg? Incidentally, why were such different vacuum pressures chosen for the two sets of tests?

It is agreed that the impulse strength of cables is dependent on the length of the butt gaps and, therefore, on the thickness of the paper used. In most oil-impregnated paper bushings, however, there are no butt gaps since the paper is wound on in one piece. The oil films are very thin, and so we should expect impulse strengths in excess of 2 000 kV/cm, based on Fig. 8. That this is not so may be due to lack of perfect voltage distribution across the capacitors under impulse stresses or due to the total thickness and volume of the dielectric, together with the effect of the higher permeability of the paper in series with the thin oil films.

Mr. W. P. Baker: In view of the importance attached by the authors to the electric strength of the impregnant it is perhaps worth considering some aspects of liquid breakdown. Recent measurements of time lags of liquid breakdown indicate that, although the formative time is very short ($<1/10\,\mu s$ for an electrode separation of 1 mm), a statistical time lag of about $2\,\mu s$ mean value might be expected between the authors' electrodes with an over-voltage of 50%.

The statistical time lags are in accordance with a simple field-emission theory and hence will be area-dependent, so that a curve of measured electric strength as a function of electrode spacing obtained by the authors' 'normal impulse technique' would tend to rise at small spacings owing to the effective reduction in cathode area.

It seems more likely that the authors' results can be explained simply on the basis of a longer breakdown path in a paper of high impermeability rather than by a consideration of a partial breakdown in the butt gap. It does not appear to be very clear how an ion moving at the rate of about $1\,\mu m/\mu s$ at a field strength of 1 MV/cm can penetrate far into the paper in the course of a 1/5 impulse wave.

Dr. B. Salvage and **Mr. J. A. M. Gibbons** (*in reply*): In reply to Mr. Mather, we do not regard the scatter in the impulse-strength measurements shown in Figs. 1 and 2 as unusual, and as stated in the paper, our conclusions were based on *t*-significance tests. It is quite possible that breakdown is initiated at the interface between the impregnant and the fibres; however, in this event it would still seem that the impregnant, rather than the fibres, breaks down first. The test temperature of 85° C for the models is the normal maximum cable conductor temperature, and testing at much higher temperatures would probably not be very realistic. With current test specifications, the impulse strength of the dielectric governs the thickness required in all modern types of pressure cable.

Regarding the effect of the paper density, we would mention that Dieterle† has very recently described experiments confirming our conclusion that super-calendering the paper causes only a small increase in impulse strength, which is attributable to the increase in the air impermeability rather than the density of the paper.

We have no evidence of oil movement from highly stressed regions of the dielectric, as mentioned by Mr. Taylor, and the short duration of the voltage impulses would seem to render any significant movement unlikely. With the 'open' test-cell it was found impracticable to filter and degas the oil for the impulse tests at a higher vacuum than 10 mm Hg.

We look forward to learning more of Mr. Baker's experiments when details are published. At present it is not clear how the dependence of the impulse strength of the impregnant on the thickness, which we have observed, is consistent with a field-emission theory and a cathode-area effect, as he suggests.

* SALVAGE, B., and GIBBONS, J. A. M.: Paper No. 3143, December, 1959 (see 107 A, p. 405).

† DIETERLE, W.: 'Beitrag zur Kenntnis der Stossfestigkeit von Isolierpapieren', *Bulletin des Schweizerischen Elektrotechnischen Vereins*, 1960, No. 13.

OBJECTIVE METHODS OF ASSESSING COMMUTATION PERFORMANCE

By J. Hindmarsh, B.Sc.(Eng.), Associate Member, and N. K. Ghai, B.Sc.(Eng.), M.Sc.Tech., Graduate.

(*Communication first received* 21*st September*, 1960, *in revised form* 11*th July, and in final form* 21*st August*, 1961.)

The need is discussed for more satisfactory methods of measuring the commutation performance of d.c. machines. Although the 'black-band' technique is valuable it is a subjective assessment, and requires considerable time and care. Consideration is therefore devoted to two objective methods for detecting the onset of sparking. Both give satisfactory results, and their appropriate fields of application are reviewed.

Introduction

The demand for d.c. machines continues to grow, and the duties they are called on to perform increase in severity. In particular, the requirements of automatic control systems involve rapid current and flux transients, thus aggravating the problem of commutation.

There is, in consequence, a revival of interest in commutation research. For the realistic appraisal of a new design or modification, it is essential that commutation performance be measured as accurately and consistently as possible. Any improvements in measurement techniques will obviously be of value, but these have been slow to develop.

Commutation Tests

Black-Band Test.—Basically the commutating ability of a machine is judged on the ultimate performance in terms of wear on brushes and commutator. Some test is required which will predict the future behaviour of the machine in this respect. The problem is formidable and at present the margin of interpole flux maladjustment which can be permitted on a new machine before it starts to spark is taken as an indication of merit commutationally. The variation of interpole current within which the machine commutates sparklessly is recorded for a series of armature currents. When plotted against armature current this sparkless zone is usually called the 'black band'.[1]

Limitations of the Black-Band Test.—There are several variables which can be adjusted on the test bed, e.g. interpole air-gap, brush coverage and brush position. By plotting black bands after each adjustment, the best settings for optimum performance can be arranged. With a lot of experience and a co-operative machine, one or two tests are sufficient for a final decision. Occasionally, however, when a wide variety of operating conditions has to be met, a large number of black-band determinations may be necessary. Further, for reliable results, the machine should be run on load for a considerable period immediately prior to each test. Test-bed time is costly and delays are frustrating to production personnel.

Black-band determinations involve a subjective judgment which may differ for different individuals. The judgment will also be affected by background lighting; black bands are noticeably narrower when taken on the nightshift. Three testers are often required, and for the one who is actually observing the commutation performance, the whole operation is often uncomfortable and even dangerous. These deficiencies in an otherwise excellent test have stimulated recent attempts to detect the onset of sparking by objective means.

Mr. Hindmarsh is, and Mr. Ghai was formerly, in the Dept. of Electrical Engineering, Manchester College of Science and Technology. Mr. Ghai is now with Lancashire Dynamo and Crypto, Ltd.

Objective Tests

The first recorded attempt was by Lundy,[2] who in 1949 used an electronic voltmeter with a large bandwidth to record the electrical noise from the machine as detected at the brush terminals. As the interpoles were 'bucked' and 'boosted', the noise increased rapidly with the commencement of sparking.

In 1956,[3] Roumanis described how, after interposing a filter to select noise frequencies higher than 36 kc/s and rectifying the output, a current of some microamperes was obtained for a slight amount of sparking, the increase of current being approximately parabolic in form when plotted against 'buck' and 'boost' current. Examples of the so-called U-curves are shown in Fig. 1. Optimum adjustment corresponds to the case where the U-curve is centred about the zero axis. Curves at no load for the adjustment of brush position, and at full load for the adjustment of interpole strength, are required.

Also in 1956, Nebolyubov[4] described the use of a photocell to 'observe' sparking, thus eliminating the subjective features of black bands taken by human eye.

The following is a brief report based on an attempt by the authors to repeat and improve on the work of Roumanis and Nebolyubov referred to above. The results may be useful to those engaged on related aspects of commutation research.

Filtered Noise Method

Roumanis Filter.—Full design information was given by Roumanis and a filter was built to his specification. The results proved disappointing. The curves resembled those of Fig. 1

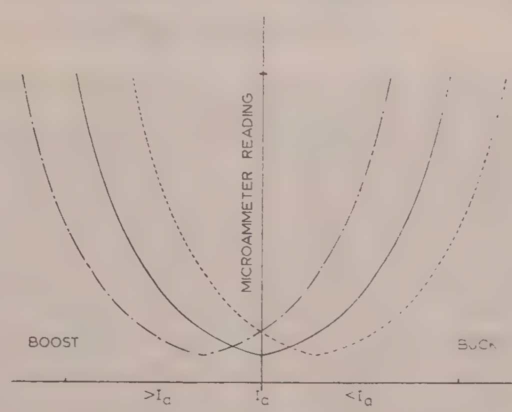

Fig. 1.—Typical U-curves. Load current I_a constant.
Interpole adjustment.
——— Optimum. — — — Weak. — — — Strong.

only vaguely and no deductions could reasonably be made from them. There was poor correlation between the onset of sparking and the noise level. (It should be noted, however, that no claims were made by Roumanis in this respect.) The filter characteristic was checked and the bottom-frequency cut-off was found to be rather lower than the quoted figure; also the attenuation in the

stop band was too low to exclude the slot ripple harmonics. Rather than spend time checking the filter in detail, a new design was prepared, this time for a more straightforward high-pass filter circuit, the bridge rectifier being sufficient to limit the upper-frequency response to about 2 Mc/s.

High-Pass Filter Design.—Before deciding on the lower- frequency cut-off, a harmonic analysis of the electrical noise was carried out under a variety of loading conditions on the two machines it was proposed to test. Fig. 2 shows two of the

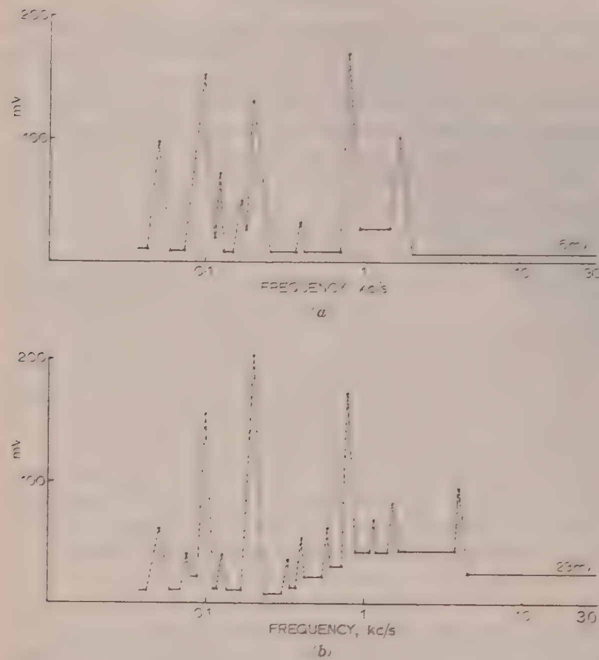

Fig. 2.—Frequency spectrum of voltage ripple on machine 1.

(*a*) 220 V full load current. No sparking.
(*b*) 220 V full load current. Slight sparking.

analyses on one of the machines; the upper limit of 30 kc/s being imposed by the measuring equipment available.

The occurrence of sparking is characterized by an increase in noise levels both generally at the higher frequencies and specifically at the lower slot-ripple harmonic frequencies. It will be noticed that the 4 kc/s voltage peak appears only during sparking (4 kc/s is the frequency at which the commutator bars break contact with the brush). The other machine had slot-ripple harmonics up to higher frequencies, and so a low-frequency cut-off at 30 kc/s was finally chosen for the filter. A few other improvements on the Roumanis design were incorporated to make the filter suitable for a variety of machines. The circuit and measured characteristic are shown on Fig. 3.

Test Results.—A selection from the many test results is shown in Figs. 4 and 5. Fig. 4 shows (*a*) the rectified total noise and (*c*) the rectified output from the Roumanis filter, compared with (*b*) and (*d*), the rectified outputs from the high-pass filter. (*a*) and (*b*) were taken when generating at normal voltage; (*c*) and (*d*) when generating on short-circuit. These readings were obtained on machine 1 which was rated at 15 hp 230 V 1 500 r.p.m. Fig. 5 shows curves taken with the high-pass filter on machine 2 rated at 10 hp 220 V 800/2 000 r.p.m., and running under a variety of conditions.

These results show that the high-pass filter gives a well-defined

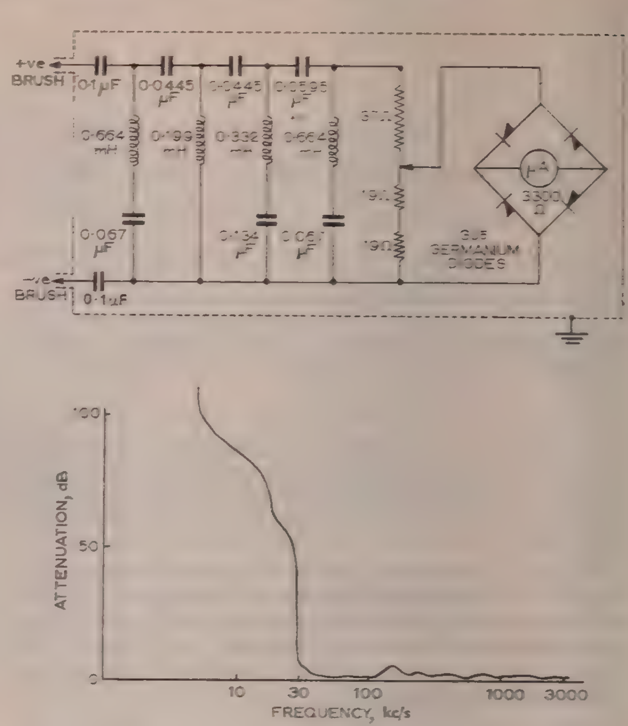

Fig. 3.—High-pass filter circuit and measured characteristic.

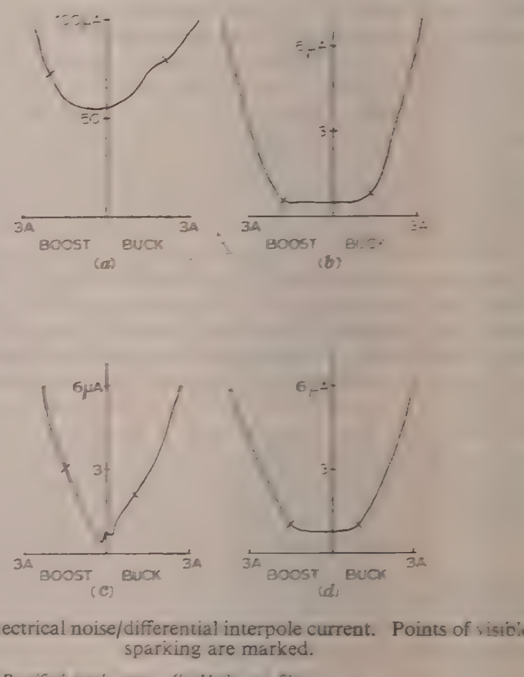

Fig. 4.—Electrical noise/differential interpole current. Points of visible sparking are marked.

(*a*) Rectified total noise. (*b*) High-pass filter.
Machine 1 running at 1 500 r.p.m. 45 A 230 V.
(*c*) Roumanis filter. (*d*) High-pass filter.
Machine 1 running at 1 500 r.p.m. 45 A short-circuit.

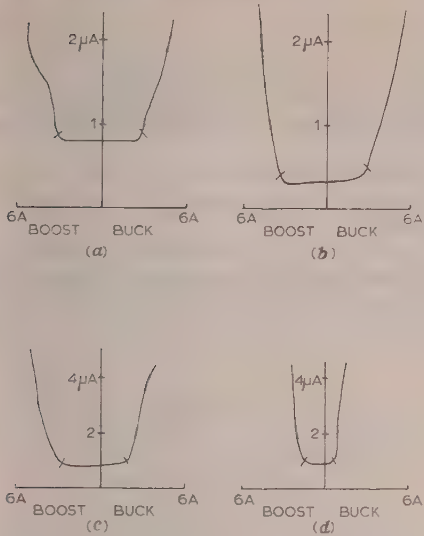

Fig. 5.—High-pass filter on machine 2. Points of visible sparking are marked.

(a) 1 000 r.p.m. 40 A 220 V. (b) 1 000 r.p.m. 40 A short-circuit.
(c) 1 500 r.p.m. 40 A 220 V. (d) 2 000 r.p.m. 40 A 220 V.

minimum output under all conditions provided that the machine is not sparking. The points of visible sparking are remarkably close to the change of microammeter reading, this being quite sharp, unlike those for the Roumanis filter. Although only two small machines were tried, the results are encouraging, but confirmation is required on a large number of machines of all sizes.

Photo-Electric Method

Initial Difficulties.—The information given in Reference 4 was insufficient to work from directly and no reports of 'teething troubles' were given. A relatively simple amplifier circuit was therefore constructed, but two severe difficulties soon arose. First, it was almost impossible to mount the photo-electric device close enough to pick up a reasonable amount of light. The solution was to use a slim Perspex light channel having one end directed quite near to the brush edge, and the other end hard up against the photo-cell mounted in a more convenient position. With suitable precautions, little light was lost in the process.

The second problem was the low signal/noise ratio, aggravated in this case by the machine being slightly out of mechanical balance. In spite of using low-microphony valves and connecting cable, the amplifier output was a few volts due to vibration alone, which was much higher than the output due to the feeble light signal. Since it was inconvenient to improve the mechanical balance, an attempt was made to deal with the difficulty in the amplifier itself.

Test Results.—By a combination of filtering and base clipping, it eventually became possible to detect the onset of sparking by means of the photocell when the amplifier output was displayed on a cathode-ray oscillograph. When the first feeble sparks appeared, sharp peaks showed up on the oscillograph screen. Base clipping on the amplifier was provided by biasing the cathode-follower output stage sufficiently below cut-off so that the residual noise was just eliminated. Actually, with this clipping circuit switched out, it was possible to detect spark-

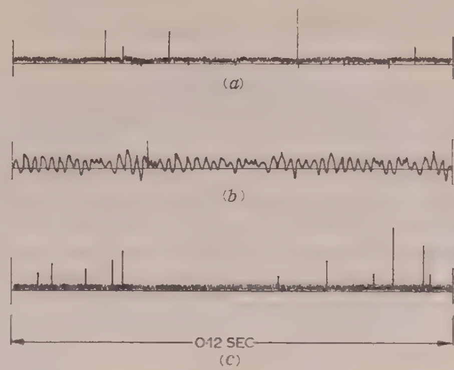

Fig. 6.—Photo-electric method. Machine sparking slightly.

(a) Photocell. Noise clipped. Oscillograph sensitivity: 1 mV/cm.
(b) Photocell. No base clipping. Oscillograph sensitivity: 1 V/cm.
(c) Photomultiplier. Oscillograph sensitivity: 0·25 V/cm.

ing just slightly greater than that at the onset. The sketch of the appropriate oscillogram given in Fig. 6(*b*) shows this condition, one spark represented by the sharp spike near the middle of the trace being clearly visible. The noise is mostly due to machine vibration. Fig. 6(*a*) was taken for the same sparking condition in order to be sure that a spark would appear while the camera was running; here the noise is clipped and the sensitivity is increased a thousandfold. Fig. 6(*c*), again for the same commutating condition, shows the output from a photomultiplier mounted in the same way as the photocell. For an alternative form of display, this output was fed through a simple transistor amplifier to a tuning indicator which flashed on and off as sparking commenced.

Since it is now obvious that many improvements can be made to the amplifier, circuit details of this are omitted here. It is sufficient to say that the overall gain was about 10^5 V/μA and that the initial sparking signals corresponded to about 10^{-7} lumen. The photocathodes chosen were of caesium antimony, since a portable spectrometer showed that the majority of the light energy was in the green region.

Comparison of Methods

The photo-electric method, while closer to the normal commutating test, requires equipment to be mounted on each brush arm of the machine. Consequently it is primarily suitable for a machine on which long-term investigations are to be made. It might be possible in certain cases to manage with only one photo-electric device supplied with light from all brushes by means of flexible light channels. A photomultiplier would then be the best proposition. In general, however, one or two light-sensitive devices would be required on each brush arm, and since one amplifier could then be used for all the photocells, this would be the cheapest arrangement and would give satisfactory performance.

The photo-electric method has the advantage that each spark can be 'seen', measured for light intensity and also located if desired. On the other hand, the high-pass filter is very simple and assesses the performance of all brush arms together without having to mount any equipment at all on the machine.

On the basis of the two machines tested, there is little to choose so far as reliability is concerned, although it is probable that over all sizes of machines the photo-electric method is better on purely technical grounds.

Both methods have the desirable features that the black band

can be taken by one person, very quickly, without discomfort, and without interference from background lighting.

ACKNOWLEDGMENTS

Since the design of d.c. machines and of electronic circuits have little in common, the authors have had to lean heavily on many of their colleagues. They are particularly indebted to Mr. F. G. Heath for his guidance when in difficulties with the amplifier, photocells and photomultipliers; and to Dr. J. Geake for his advice on the optical side and on the detection of feeble light sources. They are grateful, too, to the late Prof. E. Bradshaw for his encouragement and useful suggestions during the course of the investigation.

REFERENCES

(1) SCHROEDER, T. W., and AYDELOTT, J. C.: 'The Black Band Method of Commutation Observation', *Transactions of the American I.E.E.*, 1941, **60**, p. 446.
(2) LUNDY, R. T.: 'Measuring Commutation with an Indicating Instrument', *General Electric Review*, June, 1949, p. 29.
(3) ROUMANIS, S. J.: 'The Null Point Method of Commutation Adjustment', *Transactions of the American I.E.E.*, 1956, **75**, Part III, p. 147.
(4) NEBOLYUBOV, YU. E.: 'Photo-Electric Method of Investigating and Adjusting Commutation of Electrical Machines', *Electrichestvo*, 1956, No. 11, p. 34.

DISCUSSION ON 'THE CHARACTERISTICS AND PROTECTION OF SEMICONDUCTOR RECTIFIERS'*

WEST WALES (SWANSEA) SUB-CENTRE, 12TH JANUARY, 1961

Mr. J. W. Gibson: The best method of obtaining very high speed operation (with correspondingly low cut-off current) in a fuse for the protection of semiconductor rectifiers seems to be the use of a fuse-element in which a portion having very small cross-section is adjacent to one of large cross-section. The reduced part melts rapidly under heavy fault, while under running conditions the heavy part acts as a heat sink to maintain an adequate current rating.

The element of a conventional cartridge fuse has two widely separated thermal time-constants: the first, which depends on heat dissipation from the cartridge as a whole, is likely to be of the order of many minutes, while the second, dependent on conduction from the element to the filler in its immediate vicinity, may be about 2 sec. The rectifier fuse has a third important time-constant, dependent on interchange of heat between the two parts of the element; because of the high thermal conductivity of silver, this time-constant may be as short as 40 ms. The result is that, under fault conditions, the pre-arcing $\int i^2dt$ is not constant, but decreases with increase of fault current. Referring to Fig. 4 of the paper, this implies that, at short times, the fuse curve is less steep than for constant $\int i^2dt$ and so departs more from parallelism with the cell survival curve, which at these short times corresponds to approximately constant $\int idt$.

In Section 6 the authors refer to the arcing $\int i^2dt$ let through by the fuse. This quantity is likely to be large in relation to the pre-arcing $\int i^2dt$, particularly for the special fuses used, and the necessary margin to allow for this will be correspondingly large. Will the authors give some quantitative information on this subject? It would appear that the inherent fall in ratio of arcing $\int i^2dt$ to pre-arcing $\int i^2dt$ with reduction of fault current will to some extent rectify the departure from parallelism just mentioned.

What is the approximate increase in current rating of the fuses obtained by placing them in the air blast for cooling the rectifiers?

Messrs. D. B. Corbyn and **H. L. Potter** (*in reply*): When a rectifier fuse clears a fault in less than half a cycle, the most important factor in the protection of the diode is the peak let-through current. Provided that this current is less than the cell surge-current rating, full protection will be afforded.

The ratio between arcing and pre-arcing $\int i^2dt$ is dependent upon the operating voltage and the fuse arc voltage. In general, with special semiconductor fuses operated at the correct voltage, the arcing $\int i^2dt$ and pre-arcing $\int i^2dt$ are approximately equal.

In a 3-phase bridge equipment rated at 260 V and 4170 A, with 24 cells and fuses in parallel in each arm, the protective fuses gave the following values:

Peak let-through current ..	2960 A
Pre-arcing $\int i^2dt$	19400 A^2-sec
Arcing $\int i^2dt$	11300 A^2-sec

The determination of these values is an involved process owing to the number of variables in the circuits; the above values were calculated with the use of computers and verified by practical experiments.

Usually, no advantage is obtained by forced-air cooling the protective fuses, as they should be selected for their fault performance and not for the continuous rating. Usually the continuous rating of the fuse is in excess of the continuous rating of the cell it is protecting.

* CORBYN, D. B., and POTTER, H. L.: Paper No. 3135 U, November, 1959 (see 107 A, p. 255).

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The Institution of Electrical Engineers
Paper No. 3750 S
Dec. 1961

AN EXPERIMENTAL EFFECTIVE VALUE OF THE QUADRATURE-AXIS SYNCHRONOUS REACTANCE OF A SYNCHRONOUS MACHINE

By R. E. STEVEN, B.Sc., Ph.D., Associate Member.

(*The paper was first received* 18*th November*, 1960, *in revised form 2nd May, and in final form* 21*st August*, 1961.)

SUMMARY

The author carried out experimental tests upon two dissimilar salient-pole synchronous machines. Each machine was run as a synchronous motor on constant-voltage busbars. An examination of the results confirmed the inaccuracy which occurs in the predicted value of the load angle, δ, when the quadrature-axis reactance is assumed constant.

An original analysis of the experimental results is given whereby it is shown that the effective value of the quadrature-axis reactance can be expressed in the form

$$X_{q\,eq} = k_1 + \frac{k_q}{I(1-n)}$$

The factors involved are defined in the following way:

$k_1 = (X_d/X_q)X_1$, i.e. a function of direct-axis leakage reactance.

X_d and X_q are the conventional unsaturated values of the direct-axis and quadrature-axis reactances, obtained by, say, the slip test. X_1 is taken as equal to the Potier reactance.

n is an index determined from the open-circuit characteristic of the machine, which, it is proposed, may be interpreted in a form $V = k_f I_f^n$ over a significant part of the curve. I is the armature phase current.

The factor k_q is examined as a function which determines the effect of armature reaction, and it is shown that, in general for a synchronous machine, it may be expressed in the form

$$k_q = \frac{X_d}{K_1}\left(1 - \frac{X_1}{X_q}\right)[1 + \tan(\delta + \phi)]$$

where K_1 is a saturation factor, ϕ is the phase angle of the armature current and δ is the load angle in electrical degrees.

It is further shown that the author's expression for the effective X_q enabled accurate prediction of load angle over a range of load conditions for several machines. A derived expression for $\tan\delta$ is given which enables the prediction to be carried out by direct substitution.

LIST OF PRINCIPAL SYMBOLS

V_0 = Open-circuit, or 'excitation', voltage per phase.
V = Terminal phase voltage.
V_1 = Air-gap voltage taken on the open-circuit characteristic.
V_2 = Air-gap voltage taken at the air-gap line (corresponding to V_1).
V_d = Terminal voltage component in direction of direct axis for voltages.
V_q = Terminal voltage component in direction of quadrature-axis for voltages.
I = Armature phase current; also used for magnetizing current when related to m.m.f. effects.
I_d = Direct-axis component of armature phase current.
I_q = Quadrature-axis component of armature phase current.
I_f = Field excitation current.
X_d = Unsaturated direct-axis reactance.
X_q = Unsaturated quadrature-axis reactance.
X_p = Potier reactance.
X_1 = Armature leakage reactance, generally assumed constant.
X_{1d} = Leakage reactance on direct-axis.
X_{1q} = Leakage reactance on quadrature-axis.
X_{ad} = Reactance equivalent of direct-axis armature reaction.
X_{aq} = Reactance equivalent of quadrature-axis armature reaction.
$X_{q\,eq}$ = Experimental effective X_q.
K = Kingsley's saturation factor taken at V_1.
K_1 = Kingsley's saturation factor, using X_p instead of X_1 for V_1.
Φ = Flux.
ϕ = Phase angle (relative to V).
δ = Electrical load angle (relative to V_0).
n = Index of assumed law of open-circuit characteristic.

(1) INTRODUCTION

The two-axis principle in the theoretical analysis of synchronous machines appears to offer a truer and more realistic interpretation of the machine type.[1] Utilization of this principle in the convenient concept of the two-reaction vector diagram[1, 2] implies the necessity of knowing the true nature and magnitudes of the important machine parameters, the direct-axis and quadrature-axis reactances. Review of studies by other authors suggests that these reactances can be expressed:

$$X_d = X_1 + X_{ad} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$X_q = X_1 + X_{aq} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Refinements in the form of saturation adjustments, generally related to the air-gap voltage, V_1, and the load saturation curve, have been proposed. Accurate prediction of voltage is obtained using these quantities so refined. However, the same accuracy of prediction of load angle is not obtained.

This discrepancy in well-known prediction methods, which has been pointed out by Hamdi-Sepen[3] and others, can be attributed to the error in assuming X_q a constant. Hamdi-Sepen proposes[3] that, if the essential effects of saturation and mutual influences are introduced, the appropriate coefficients appear in the reactance tensor. The factors necessary to the application of his prediction method require particular experimental facilities for their determination, and the subsequent prediction of load angle employs an iterative method of solution.

The paper describes an attempt to determine an expression for the experimental effective value of the parameter $X_{q\,eq}$ which will also satisfy the form of the two-reaction vector diagram. The argument is based partly on theoretical considerations, but essentially satisfying experimental data. Prediction of load angle is thereby obtained by direct substitution using conventional test data of the machine.

(2) ANALYSIS OF EXPERIMENTAL MACHINE NO. 1

(2.1) Specification and Tests

Experimental machine No. 1 was a salient-pole rotating-field a.c. generator specified as follows:

Continuous rating 10 kVA, 346/200 V, 16·7 A,
p.f. 0·8, 1 000 r.p.m., 3-phase, 50 c/s.

All the instruments used in the tests were calibrated using a co-ordinate a.c. potentiometer of the Gall type, laboratory standards of resistance and a Weston standard cell.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Dr. Steven is in the Electrical Engineering Department, University of Southampton.

The tests on machine No. 1 were conventional and included:

(i) Determination of open-circuit and short-circuit characteristics.
(ii) Loading at zero power-factor to determine Potier reactance.
(iii) Slip test, for determination of unsaturated values of X_d and X_q: values were checked by the maximum-lagging-current test,[4] and also by the reluctance-torque method.[5]
(iv) Load tests on the machine operating as a synchronous motor on constant-rated-voltage busbars for variable excitation, constant load conditions, i.e. determination of the so-called V-curves of armature current, but also power factor and load angle measurement.

The results of tests (i)–(iv) are the basis of much of the ensuing discussion. In addition, a direct load test was made on the machine operating as a synchronous generator, the results being used to check the accuracy of load angle prediction.

(2.2) Experimental Effective X_q

Assuming that the vector disposition of the two-reaction principle is valid, but that the reactances X_d and X_q are variables, it is possible to calculate the effective values of X_q, in particular, using experimental results obtained by direct test.

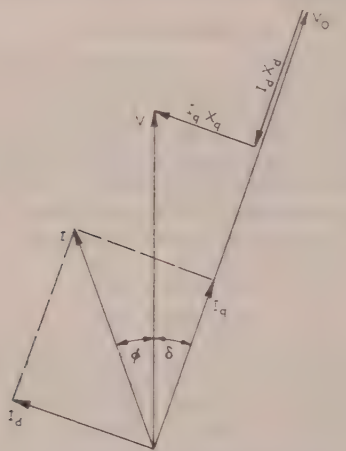

Fig. 1.—Two-reaction vector diagram of a synchronous motor, leading armature current.

From the vector diagram, Fig. 1,

$$X_q = \frac{V \sin \delta}{I_q} = \frac{V \sin \delta}{I \cos (\delta + \phi)} \quad . \quad . \quad . \quad . \quad (3)$$

Substituting experimental values in this equation the author obtained a succession of values for effective X_q for experimental machine No. 1, for various conditions of loading and at various excitations. The essential results in this context are shown plotted in Fig. 2, which shows the variation of effective X_q with field current for various fixed loadings.

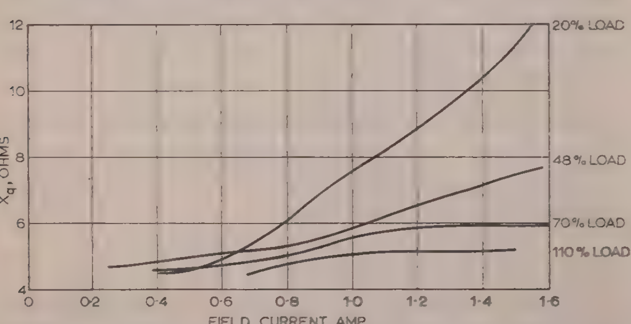

Fig. 2.—Experimental effective values of X_q for machine No. 1.

The following observations may be made regarding this diagram:

(i) At low values of excitation, at all loads, the effective value of X_q tends towards the unsaturated value, which for machine No. 1 was 4·6 Ω.
(ii) Under conditions of fairly heavy load and over a wide range of excitation, the effective value of X_q shows a tendency to remain fairly constant at the unsaturated value. A slight tendency to increase is indicated at higher values of excitation, i.e. in the case of a synchronous motor, for leading armature current.
(iii) The tendency to increase at the higher values of excitation becomes more marked under conditions of light loading.

(2.3) Further Inquiry at the Condition $\delta = \phi$

A special case occurs when $\delta = \phi$. Then the direct-axis component of armature current, I_d, becomes zero, leaving only I_qX_q as the effective reactance drop.[6] Under this condition a simple relation holds, namely

$$X_q = \frac{V \sin \delta}{I} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and, theoretically at least, effects due to I_d are removed.

The appropriate experimental values at this condition are obtained by plotting δ and ϕ to a common field-current base, Fig. 3. The results so determined are detailed in Table 1, and

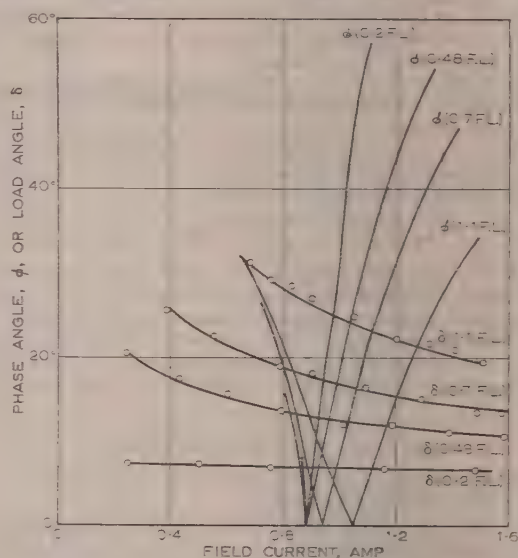

Fig. 3.—Determination of experimental data at the condition $\delta = \phi$, for machine No. 1.

Table 1

EXPERIMENTAL RESULTS ON MACHINE 1 FOR $\delta = \phi$

Approximate load	$\delta = \phi$	I_f	I	$\sin \delta$	$X_{q\,eq}$
%	elec. deg.	A	A		Ω
20	7·0	0·88	3·8	0·122	6·4
48	13·5	0·83	8·5	0·2335	5·5
70	19·0	0·79	12·8	0·326	5·0
110	31·6	0·66	22·8	0·524	4·6

for this machine indeed suggest a possible inverse proportional relation between effective X_q and load current, Fig. 4.

A guide as to this relationship was sought on the following simple lines:

Let
$$X_q = \omega \frac{N\Phi}{I} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

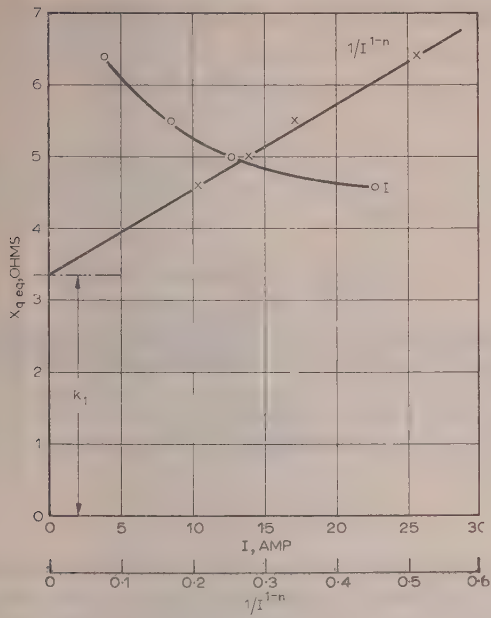

Fig. 4.—Relationship between X_{qeq} and I at the condition $\delta = \phi$ for machine No. 1.

Allowing for saturation, and with armature current as the magnetizing current, flux is some function of current:

$$\Phi = f(I) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Now a simple power law is assumed for the magnetization curve, of a general form

$$V = k_f I_f^n \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

With armature current as the magnetizing current, we may write

$$\Phi = k_a I^n \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Returning to eqn. (5) and substituting for Φ as in eqn. (8),

$$X_q = \frac{\omega k_a I^n N}{I} \propto \frac{1}{I^{(1-n)}} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

A suitable value for the index n over a significant part of the magnetization curve is obtained by plotting the open-circuit characteristic on log/log paper. For machine No. 1 a value of $n = 0 \cdot 5$ was decided upon. Using experimental results corresponding to the $\delta = \phi$ condition, values of $1/I^{1-n}$ were obtained and plotted in Fig. 4. The straight-line relation is considered to be significant since it implies that

$$X_{qeq} = k_1 + \frac{k_2}{I^{(1-n)}} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where k_1 and k_2 are constants.

(2.4) Examination of the Constant k_1

Now generally it is considered[2, 7] that

$$X_q = X_1 + X_{aq} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Comparison of eqns. (10) and (11) would suggest that

$$X_{aq} = \frac{k_2}{I^{(1-n)}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

The other implication is that the constant k_1 is the leakage reactance, X_1, which is usually assumed constant.

Now X_1, it has been suggested,[8] may be taken as equal to the Potier reactance. The experimental value of $X_p = 1 \cdot 92\,\Omega$ was obtained. This is not in agreement with the value of $k_1 = 3 \cdot 35$, obtained from Fig. 4. It was thought significant that the ratio k_1/X_1 is $3 \cdot 35/1 \cdot 92 = 1 \cdot 75$, while the ratio of the unsaturated values of X_d and X_q for the same machine is $8 \cdot 2/4 \cdot 6 = 1 \cdot 78$. This agreement could be interpreted as meaning that

$$k_1 = \frac{X_d}{X_q}(X_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Summarizing at this stage, it appears that:

(i) The effective X_q consists of two parts: one is proportional to $1/I^{(1-n)}$, where n is defined in relation to an assumed power law for the open-circuit characteristic of the machine; the other part is a constant.

(ii) The constant part is not equivalent to the constant which is usually interpreted as the reactance equivalent of armature leakage, X_1. It is, however, possible that armature leakage on the quadrature axis is related to that which occurs on the direct axis, in the ratio of the unsaturated X_d to the unsaturated X_q.

Hence it is proposed at this stage that

$$X_{qeq} = \frac{X_d}{X_q}(X_1) + \frac{k_2}{I^{(1-n)}} \quad . \quad . \quad . \quad . \quad (14)$$

(3) ADDITIONAL EXPERIMENTAL STUDY OF $X_{q\,eq}$

(3.1) Experimental Machine No. 2

This machine was specified as follows:

Rotating armature a.c. generator, 10 kW, 134 V, 50 c/s, 1 500 r.p.m., 3-phase, delta connected.

Tests similar to those detailed in Section 2.1 were carried out on this machine and the data pertinent to the study of $X_{q\,eq}$ were examined. The same high order of accuracy is not claimed, but the tendencies exhibited are felt to be worthy of inclusion.

Experimental values of X_{qeq} were obtained using eqn. (3), and the result is demonstrated in Fig. 5. General tendencies

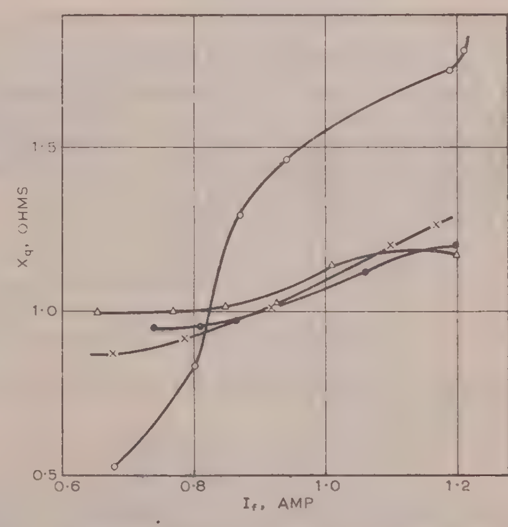

Fig. 5.—Experimental effective values of X_q for machine No. 2.

○ 0·23 f.l.
× 0·48 f.l.
● 0·68 f.l.
Δ 0·71 f.l.

similar to those obtained for machine No. 1 will be noted, namely:

(i) At low values of excitation X_{qeq} tends towards a constant value. But for the load conditions considered, this is less than unsaturated X_q, in this case $1{\cdot}14\,\Omega$, and for light loading X_{qeq} continues to decrease in a marked way at small values of excitation.

(ii) The tendency to maintain a near-constant value over a wide range of excitation is more marked as the load is increased; it is thought reasonable to conjecture that, for full-load conditions, this would approximate to the unsaturated value of X_q.

(iii) The tendency to increase at higher values of excitation is apparent.

(3.2) Inquiry at $\delta = \phi$ Condition for Machine No. 2

The appropriate experimental results for this machine are given in Table 2. To determine a suitable value for the index n, the open-circuit characteristic was plotted on log/log paper and the operating point was taken at the air-gap voltage. This was calculated using X_p instead of X_1.

Table 2

EXPERIMENTAL RESULTS ON MACHINE NO. 2 FOR $\delta = \phi$

Approximate load	$\delta = \phi$	I	$X_{q\,eq}$	Index n	$1/[I^{(1-n)}]$
%	elec. deg.	A	Ω		
23	3·2	5·0	1·49	0·8	0·725
48	5·2	12·0	1·02	0·6	0·37
68	7·2	17·1	0·98	0·6	0·32
71	7·9	18·0	1·02	0·6	0·315

The graph showing the relation between $X_{q\,eq}$ and $1/[I^{(1-n)}]$ was a straight line and supports the suggestion that eqn. (10) is valid. Further, for this machine the Potier reactance X_p as measured was $0{\cdot}355\,\Omega$. Thus the proposed X_{1q} becomes

$$X_{1q} = \frac{X_d}{X_q}(X_1) = \frac{1{\cdot}78}{1{\cdot}14}(0{\cdot}355) = 0{\cdot}552\,\Omega.$$

The intercept k_1 on the graph in this case agrees reasonably.

(4) STUDY IN RELATION TO OTHER PROPOSALS

(4.1) Hamdi-Sepen's Proposals

It is generally accepted[8] that the degree of saturation is determined by the air-gap flux, a measure of which is given by the 'voltage behind leakage reactance', or air-gap voltage. Quantitatively a saturation factor, K, was proposed by Kingsley,[9] and calculated as the ratio V_2/V_1.

This proposal, applied to eqn. (1), gives

$$\text{saturated } X_{ad} = \frac{X_d - X_1}{K} \qquad (15)$$

$$\text{saturated } X_d = X_1 + \frac{X_d - X_1}{K} \qquad (16)$$

Hamdi-Sepen[3] examines this proposal in the following manner. In the case of saturation,

$$V_0 = V + j\left(X_1 + \frac{X_d - X_1}{K}\right)I \qquad (17)$$

$$V = V_0 - j\left(X_1 + \frac{X_d - X_1}{K}\right)I$$

$$= V_0 - j\frac{X_d}{K}\left[\frac{X_1}{X_d}(K-1) + 1\right]I \qquad (18)$$

For the non-salient-pole case, the axis components of V are

$$V_q = V_0 - \frac{X_d}{K}\left[\frac{X_1}{X_d}(K-1) + 1\right]I_d \qquad (19)$$

$$V_d = -\frac{X_d}{K}\left[\frac{X_1}{X_d}(K-1) + 1\right]I_q \qquad (20)$$

Eqn. (19) is rewritten

$$V_q = \frac{X_d}{K}\left\{\frac{KV_0}{X_d} - \left[\frac{X_1}{X_d}(K-1) + 1\right]I_d\right\} \qquad (21)$$

The coefficient of I_d is close to unity and it is assumed to be equal to unity. With this simplification eqns. (20) and (21) become

$$V_q = \frac{X_d}{K}\left[\frac{KV_0}{X_d} - I_d\right] \qquad (22)$$

$$V_d = -\frac{X_d}{K}I_q \qquad (23)$$

By expressing these equations in tensor form it is noted that the antidiagonal terms in the reactance matrix are zero, indicating no mutual influence between the two axes, which is the hypothesis of the two-reaction theory.

Hamdi-Sepen modifies this mathematical form to cater for the salient-pole case, and also in relation to his experimental work. Coefficients are introduced in the vacant antidiagonal positions, to cater for the mutual axis influence, giving:

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} \frac{X_d}{K_d} & \xi_{qd} \\ \xi_{dq} & \frac{X_q}{K_q} \end{bmatrix} \times \begin{bmatrix} \frac{KV_0}{X_d} \pm I_d \\ -I_q \end{bmatrix} \qquad (24)$$

(4.2) Relationship to the Present Author's Proposal

The present author decided to retain the coefficient of I_q, and for the salient-pole case to replace X_d by X_q. But the multiplier X_d/K, eqn. (20), was retained in view of the nature of eqn. (14), suggested by experiment. Hence it is proposed that

$$V_d = -\frac{X_d}{K}\left[\frac{X_1}{X_q}(K-1) + 1\right]I_q \qquad (25)$$

$$= -I_q X_{q\,eq}$$

Then

$$X_{q\,eq} = \frac{X_d}{K}\left[\frac{X_1}{X_q}(K-1) + 1\right]$$

$$= \frac{X_d}{X_q}X_1 + \frac{X_d}{K}\left(1 - \frac{X_1}{X_q}\right) \qquad (26)$$

Comparing this with eqn. (14), it is implied that

$$\frac{k_2}{I^{(1-n)}} = \frac{X_d}{K}\left(1 - \frac{X_1}{X_q}\right) \qquad (27)$$

Now, the quantities X_d, X_q and X_1 in this context are constants. Further, it has been shown by experimental data, Fig. 4, that k_2, which is the slope of the straight-line graph, is a constant. Thus, from eqn. (27), it may be stated that K should be proportional to $I^{(1-n)}$. This is explored as follows:

K is defined as the ratio V_2/V_1. In terms of an assumed power

law for the open-circuit characteristic, say $V_1 = AI^n$, and a law for the air-gap line, $V_2 = BI$, where A and B are constants, then

$$K = \frac{BI}{AI^n} = \frac{B}{A} I^{(1-n)} \quad . \quad . \quad . \quad . \quad . \quad (28)$$

where I is the magnetizing current.

In the final issue it should be noted that $I^{(1-n)}$ is a dimensionless ratio in this context.

(5) EXAMINATION OF THE 'CONSTANT' k_2

(5.1) The Condition $\delta \neq \phi$

A measure of support for the proposed expression for X_{qeq}, eqn. (14), having been obtained, it is important to remember that, so far, the experimental support has been confined to the condition $\delta = \phi$, i.e. when I_d is zero. Thus it would be more correct in this case, since X_{qeq} is subject to I_q alone, to restate eqn. (14):

$$X_{qeq} = \frac{X_d}{X_q} X_1 + \frac{k_2}{I_q^{(1-n)}} \quad . \quad . \quad . \quad . \quad (29)$$

This expression might be written in a more general form:

$$X_{qeq} = X_{1q} + X_{aq} \quad . \quad . \quad . \quad . \quad . \quad (30)$$

If the armature current is to be I instead of I_q, the new effective value of k_2, say k_q, might be written

$$\begin{aligned} k_q &= I^{(1-n)} X_{aq} \\ &= I^{(1-n)}(X_{qeq} - X_{1q}) \quad . \quad . \quad . \quad . \quad (31) \end{aligned}$$

On the basis of this proposal the values of k_q have been evaluated for various conditions of loading over a range of excitation, using the experimental results of machine No. 1.

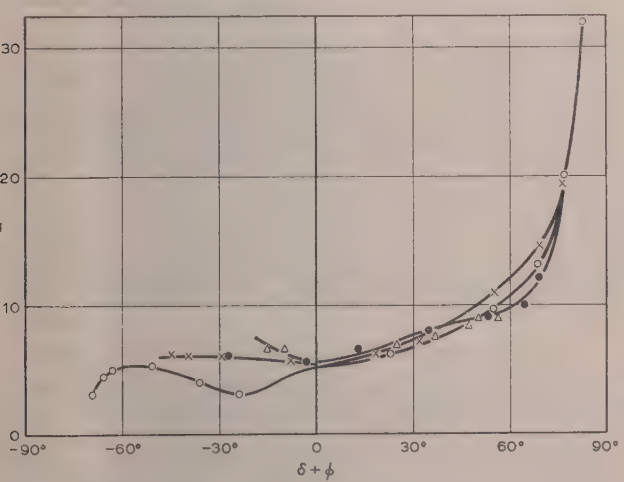

Fig. 6.—Determination of relationship between k_q and effective angle of armature reaction.

○ 0·2 f.l.
× 0·48 f.l.
● 0·7 f.l.
△ 1·1 f.l.

In Fig. 6 experimental k_q is shown plotted against angle $(\delta + \phi)$, the effective angle of armature reaction. The relation which was so determined was examined and it was verified that a close agreement occurs at all loadings when

$$k_q = k_2[1 + \tan(\delta + \phi)] \quad . \quad . \quad . \quad (32)$$

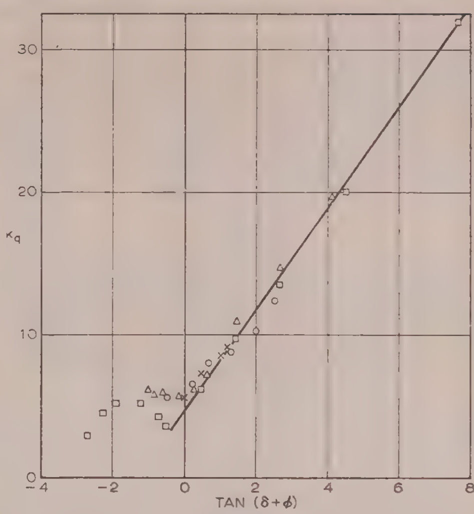

Fig. 7.—Verification of relationship between k_q and $(\delta + \phi)$.

□ 0·2 f.l.
△ 0·48 f.l.
○ 0·7 f.l.
× 1·1 f.l.

Values of k_q are shown plotted against $\tan(\delta + \phi)$ in Fig. 7, and a straight-line law is evident. The slope of the straight line and the intercept at $\tan(\delta + \phi) = 0$ are seen reasonably to be of the same value, namely the value of k_2 as determined with $\delta = \phi$. But when $\tan(\delta + \phi)$ becomes negative a measure of departure from the straight line occurs and another factor affecting the k_2 part of k_q was sought.

(5.2) The 'Constancy' of k_2

It might now be stated that

$$\begin{aligned} X_{qeq} &= \frac{X_d}{X_q} X_1 + \frac{k_q}{I^{(1-n)}} \\ &= k_1 + \frac{k_2[1 + \tan(\delta + \phi)]}{I^{(1-n)}} \quad . \quad . \quad (33) \end{aligned}$$

but with a query whether k_2 remains the constant implied in eqn. (27) when the current is not I_q. Experimental values of k_2, calculated using the form of eqn. (33) and machine No. 1 results, are shown in Fig. 8 and a variation is apparent. The suggestion is that a coefficient must be introduced which is close to unity. The author decided to introduce a saturation factor in the manner of Kingsley's coefficient, K, but taken at an air-gap voltage calculated using X_p instead of X_1. This decision might be justified on the assumption that increasing saturation on the direct axis will tend to divert more armature flux from the quadrature-axis path, thus affecting X_{aq} in an inverse fashion.

With this modification the value of k_2 becomes

$$k_2 = \frac{X_d}{K_1}\left(1 - \frac{X_1}{X_q}\right) \quad . \quad . \quad . \quad . \quad (34)$$

(6) X_{qeq} AND LOAD ANGLE PREDICTION

(6.1) Final Form of X_{qeq}

Summarizing the above deliberations the author proposes the following expression for the experimental quadrature-axis synchronous reactance:

$$X_{qeq} = \frac{X_d}{X_q} X_1 + \frac{X_d}{K_1}\left(1 - \frac{X_1}{X_q}\right)\frac{1 + \tan(\delta + \phi)}{I^{(1-n)}} \quad . \quad (35)$$

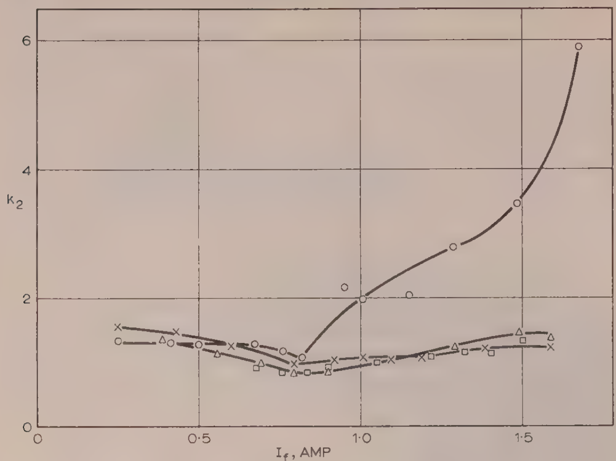

Fig. 8.—Examination of the constancy of k_2.
○ 0·2 f.l.
× 0·48 f.l.
△ 0·7 f.l.
□ 1·1 f.l.

This expression can be put in simplified forms:

$$X_{qeq} = k_1 + \frac{k_2[1 + \tan(\delta + \phi)]}{I^{(1-n)}} \quad . \quad . \quad . \quad . \quad (36)$$

$$= k_1 + \frac{k_q}{I^{(1-n)}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

(6.2) Solution for Load Angle by Iterative Substitution

The proposed expression for X_{qeq} contains two unknowns, namely $X_{q\,eq}$ and δ. A form of iterative substitution may be used since the value of δ must, by hypothesis, give the same value of X_{qeq} as that obtained using the geometrical form of the two reaction vector diagram, i.e.

$$X_{qeq} = \frac{V \sin \delta}{I \cos(\delta + \phi)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

This method of solution for δ, using conventional constants and specified conditions of operation of machine No. 1, is demonstrated in Fig. 9.

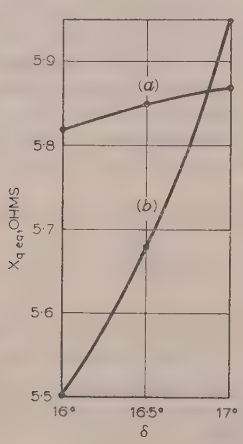

Fig. 9.—Solution for δ by iterative substitution.
(a) Author's method.
(b) Two-axis theory.

(6.3) Solution for Load Angle by Direct Substitution

By equating the two expressions given for $X_{q\,eq}$ in eqns. (36) and (38) a solution is obtained for $\tan \delta$, namely

$$\tan \delta = \frac{k_1 I \cos \phi + k_2 I^n (\sin \phi + \cos \phi)}{V + k_2 I^n (\sin \phi - \cos \phi) + k_1 I \sin \phi} \quad . \quad (39)$$

Hence it is proposed that δ may be determined for any specified condition of operation of a synchronous machine from a knowledge of the conventional constants which determine k_1 and k_2, as defined in eqns. (13) and (34) respectively, and using the open-circuit characteristic which determines the index n.

(7) EXPERIMENTAL CHECK ON PREDICTION ACCURACY

(7.1) Direct Test on Machine No. 1 as a Generator

Values for the conventional constants involved in eqn. (39) were obtained for machine No. 1, from which the appropriate values of k_1 and k_2 were calculated. Prediction was made of δ for a range of load currents at the rated terminal voltage and power factor. These values of δ were compared with those measured by direct test, Fig. 10. In this diagram are also shown the predicted values of δ obtained using two well-known methods, generally known as the synchronous impedance method[10] and that due to S. B. Crary and others.[8]

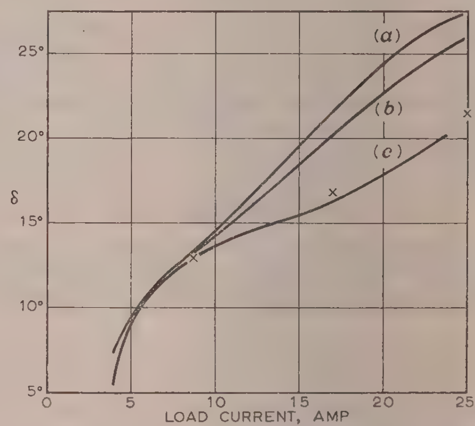

Fig. 10.—Comparison of load angle prediction for machine No. 1 as a generator, p.f. 0·8 lagging, by different methods.
(a) Synchronous-impedance method.
(b) Crary's method.
(c) Direct test.
× By author's X_{qeq}.

(7.2) Prediction of δ for Hamdi-Sepen's 15 kVA Machine

In Hamdi-Sepen's paper[3] values are given for the necessary conventional constants required by the present author's expression for $\tan \delta$. Using these values and working to the limited accuracy afforded by the printed reproduction of the open-circuit characteristic of the machine, a good accuracy of prediction of δ was achieved. The comparison is given in Table 3.

Table 3

PREDICTION FOR 15 kVA MACHINE

Method	Load angle elec. deg.
Blondel diagram, using X_1	35
Potier diagram	41·7
American Standards Association	49·2
Hamdi-Sepen	23
Direct test	23 23·5
Present author	25·1

Direct test of one load only was given, namely full load at unity power factor.

(7.3) Prediction of δ for Hamdi-Sepen's 7 kW Machine

Test figures obtained by Hamdi-Sepen[11] for a 7 kW 110/190 V a.c. generator for a wide range of load conditions were examined by the present author. A representative selection of the values obtained by direct test are given in Table 4, and predicted values of δ obtained by the present author are compared. It will be noted that the values of n and K_1 are given, indicative of the accuracy sought.

Table 4

COMPARISON OF AUTHOR'S PREDICTED δ WITH MEASURED VALUES FOR HAMDI-SEPEN'S 7 KW MACHINE

Direct test values			Author's values			Vector diagram using unsaturated X_q
I	ϕ	δ	n	K_1	Predicted δ	Predicted δ
A						
10	−46·5	4·8	0·35	1·35	4·6	12·0
10	0	9·0	0·35	1·27	9·9	14·0
10	+46·9	8·0	0·45	1·2	9·0	8·9
15	−45·0	6·6	0·30	1·4	7·5	18·7
15	0	13·0	0·35	1·27	13·2	20·2
15	+46·1	13·4	0·45	1·2	12·2	11·9
20	−45·0	8·1	0·3	1·52	10·3	27·2
20	0	16·0	0·35	1·27	16·7	26·0
20	+44·5	19·0	0·60	1·15	18·7	15·0
25	0	18·6	0·3	1·29	18·9	32·2
25	+45·0	24·0	0·65	1·1	23·5	17·0

(7.4) Prediction of δ for Hamdi-Sepen's 10 kVA Machine

This was a 120/208 V machine operated as a generator with a unity power factor load but at different loadings and different terminal voltages, i.e. different values of excitation.[12] The test value of X_p was supplied to the present author by Professor Hamdi-Sepen, together with a more accurate graph of the open-circuit characteristic. Values of δ were calculated by the present author and compared with those test values singled out in the paper[12] as representing a mean of many test results. It may be noted that $X_p = 0{\cdot}308\,\Omega$. The comparison between the direct test results and the present author's predicted δ are given in Table 5.

Table 5

COMPARISON OF AUTHOR'S PREDICTED δ WITH MEASURED VALUES FOR HAMDI-SEPEN'S 10 KVA MACHINE

Direct test values			Author's values			Vector diagram using unsaturated X_q
V	P	δ	n	K_1	Predicted δ	Predicted δ
per unit	per unit					
0·75	0·35	8·3	0·6	1·06	8·2	9·8
0·75	0·5	11·6	0·6	1·06	11·3	13·2
0·75	0·65	14·6	0·6	1·06	14·1	17·0
0·92	0·40	5·7	0·55	1·2	5·4	7·2
0·92	0·60	8·1	0·55	1·2	7·7	10·5
0·92	0·80	10·1	0·55	1·3	9·8	13·9

(7.5) Prediction of δ for Edinburgh 12 kVA Machine

Experimental test results for this machine, operating as a synchronous motor on constant-voltage 420 V busbars, were kindly supplied to the author by Professor Openshaw-Taylor of the Heriot-Watt College, Edinburgh. The machine was star connected and had the following constants:

$$X_d = 11{\cdot}85\,\Omega,\ X_q = 8{\cdot}21\,\Omega \text{ and } X_p = 3{\cdot}8\,\Omega.$$

Table 6

COMPARISON OF AUTHOR'S PREDICTED δ WITH DIRECT TEST VALUES FOR EDINBURGH 12 KVA MACHINE

Direct test values				Author's values			Vector diagram using unsaturated X_q
I	P	ϕ	δ	n	K_1	δ	δ
A	kW						
4·3	2·72	−29·6	7	0·8	1·1	7·5	8·0
8·4	5·85	−16·2	16	0·75	1·1	18·1	16·4
10·4	7·05	−20·7	21	0·75	1·1	21·8	21·8
12·8	8·6	−22·3	25	0·70	1·11	26·0	26·0
16·5	10·7	−26·5	35	0·70	1·11	34·0	33·8

(8) CONCLUSIONS

Although the proposed expression for $X_{q\,eq}$ gives satisfactory results for the cases considered, it is recognized that these are for small experimental machines. The proposal has not been checked for large machines. Consequently it is felt that it can be offered only as an academic contribution to the theory of synchronous machines, largely of an empirical nature. However, it is hoped that it will direct attention to factors helpful to the solution of the elusive conditions obtaining in the air-gap of a loaded synchronous machine.

It is of interest to note that conclusions can be drawn which are in agreement with those of Hamdi-Sepen,[3] namely:

(i) The resultant flux component along a given axis is influenced by the ampere-turn component acting along the other axis.
(ii) The ratio of the ampere-turn components, namely $\tan(\delta + \phi)$ affects the operating conditions of the machine.

In addition, the experimental results

(iii) Confirm that the axis reactance consists of two parts, one constant and the other depending on the armature current and on the measure of saturation on the direct axis as determined by the air-gap voltage.
(iv) Show that the leakage reactance on the quadrature axis is related to that on the direct axis in the inverse ratio of the unsaturated axis reactances.
(v) Show that, for a machine with very little saturation, the two-reaction vector diagram using the unsaturated value of X_q can provide satisfactory prediction of δ [Table 6]. However, where the machine is subject to considerable saturation, inaccuracy occurs in predicted δ [Tables 4 and 5]. The influence of increasing saturation is further demonstrated by the greater errors obtained for similar current loadings at different excitations [Table 5].

(9) ACKNOWLEDGMENTS

The author is indebted to Professor L. G. A. Sims of Southampton University for consistent encouragement in a field of research which has so extensively been explored; also to Professor T. P. Allen of the Queen's University of Belfast, who introduced the author to the fascinations of the two-reaction theory of synchronous machines. Thanks are expressed to Professor D. Hamdi-Sepen of the Technical University, Istanbul,

Turkey, and to Professor Taylor of the Heriot-Watt College, Edinburgh, for supplying test data.

Part of the experimental work was carried out by the author at the College of Technology, Belfast, and the author wishes to thank Mr. J. Fitton, M.Sc., for permission to use the laboratory facilities.

(10) REFERENCES

(1) Adkins, B.: 'The General Theory of Electrical Machines' (Chapman and Hall, 1957).

(2) Doherty, R. E., and Nickle, C. A.: 'Synchronous Machines, I and II', *Transactions of the American I.E.E.*, 1926, **45**, p. 912.

(3) Hamdi-Sepen, D.: 'Saturation Effects in Synchronous Machines', *ibid.*, 1954, **73**, Part III B, p. 1349.

(4) Sheperd, R. V., and Kilbourne, C. E.: 'The Quadrature-Axis Reactance of the Salient-Pole Synchronous Machine', *ibid.*, 1943, **62**, p. 684.

(5) Kingsley, C., Jr.: 'Measurement of Quadrature-Axis Reactance', *ibid.*, 1935, **54**, p. 572.

(6) Steven, R. E.: 'Prediction of Salient-Pole Synchronous Machine Performance Using the Two-Reaction Theory', *Bulletin of Electrical Engineering Education*, 1957, **18**, p. 16.

(7) Alger, P. L.: 'Calculation of Armature Reactance of Synchronous Machines', *Transactions of the American I.E.E.*, 1928, **47**, p. 493.

(8) Crary, S. B., Shildneck, L. P., and March, L. A.: 'Equivalent Reactance of Synchronous Machines', *ibid.*, 1934, **53**, pp. 124 and 603.

(9) Kingsley, C., Jr.: 'Saturated Synchronous Reactance', *ibid.*, 1935, **54**, p. 300.

(10) Behn-Eschenburg, H.: 'Über den Spannungsabfall in Wechselstromgeneratoren', *Elektrotechnischen Zeitschrift*, 1904, **20**, Seite 397.

(11) Hamdi-Sepen, D.: 'Une méthode d'analyse du fonctionnement de la machine synchrone en régime établi', *Revue Générale de l'Electricité*, 1953, **62**, p. 442.

(12) Hamdi-Sepen, D.: 'Contribution a l'étude expérimentale des déclages internes des machines synchrones. Influence de la saturation', *ibid.*, 1951, **60**, p. 107.

RECENT DEVELOPMENTS IN MAGNETIC WORK-HOLDING DEVICES FOR MACHINE TOOLS

By J. C. Jones, Member.

(*Communication received 22nd August*, 1961)

The electromagnetic chuck has, of course, been in regular use, particularly on grinding and milling machines, for a long period. Whilst it provides a most satisfactory method of holding ferrous workpieces, it has the disadvantage that an unexpected failure of the electricity supply may cause the workpiece to be thrown off the machine with the attendant risk of damage to the machine and injury to the operator. This somewhat remote risk can be obviated by having an auxiliary storage battery floating across the chuck terminals, but this method is expensive and difficult to maintain in a reliable condition in the average machine shop. The other disadvantage relates to the method of demagnetization. Until recently it has been usual to employ a double-pole change-over switch with mid 'off' position and suitable discharge resistors. In order to demagnetize the workpiece the operator had to estimate the length of time during which the switch was held in the 'demagnetize' position so as to be able to release the workpiece easily from the chuck. Whilst this was fairly satisfactory for cast iron and mild steels, with hardened tool steels having a high magnetic remanence, it was often necessary to provide channels in the chuck face so that the workpiece could be levered away from it after demagnetization. To overcome this disadvantage a push-button-operated demagnetizer has recently been developed, its object being to inject a succession of decreasing reverse and forward pulses into the exciting coils, chuck poles and workpieces, and to make the demagnetizing process automatic. The chuck poles and their existing coils form a highly inductive circuit and their impedance to alternating current is so high that it is not possible to pass sufficient current through the coils at a power frequency of 50 or 60 c/s for demagnetization purposes, as might at first sight seem possible. Experimental work indicated that it is necessary to use current pulses of decreasing amplitude at a frequency of about 0·5 c/s in order to provide satisfactory demagnetization of all types of workpiece.

The control system has been designed to operate from an a.c. supply rather than an auxiliary workshop d.c. supply, since the former is always available at the machine tool itself. The extremely high inductance of the chuck windings makes reliable switching of the exciting direct current difficult. Accordingly the control system includes a transformer and metal rectifier, the secondary of the transformer having a number of tappings which, when connected through the rectifier, give a number of steps of reduced output direct voltage. These transformer tappings are connected through a motor-driven tap-changing

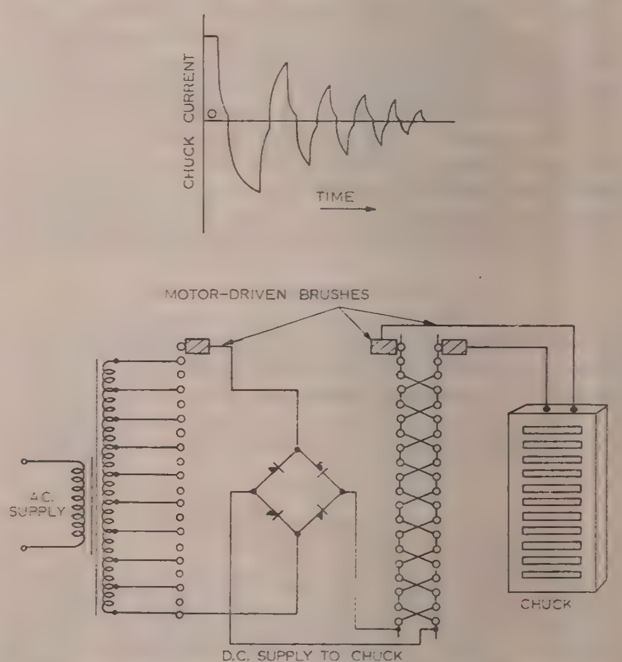

Fig. 1.—Electromagnetic chuck demagnetizing pulses, and schematic of control system.

Mr. Jones is with the Churchill Machine Tool Co., Ltd.

switch, having one set of contacts for changing the transformer tappings and another set for reversing the direction of the chuck exciting current at the moment the a.c. input to the rectifier is disconnected, as shown in Fig. 1. A non-linear discharge resistor is connected across the chuck winding in order to absorb the inductive discharge which occurs whilst switching. The continued rotation of the tapping switch disconnects the a.c. supply to the rectifier, reverses the chuck d.c. connections and then reconnects the a.c. supply on a lower tapping until the fully demagnetized condition is reached by passing through the diminishing demagnetizing and magnetizing pulses indicated in Fig. 1. The workpiece is therefore left with the minimum of residual magnetic flux, and can be easily removed from the chuck face.

A later development was the introduction of the permanent-magnet chuck, which was designed to avoid the risk of work release due to failure of the excitation of an electromagnetic chuck and to obviate the need for flexible connecting leads or for slip-rings and brushes connecting the moving chuck to stationary parts of a machine tool. This type of chuck produces as great a holding power as the electromagnetic type, the principle of flux diversion illustrated in Fig. 2 being used. It will be seen that the flux path through the permanent magnet itself is never broken, but diverted by a sliding keeper, ensuring that the flux density of the permanent magnets is preserved. This type of chuck can, however, be magnetized only after having been completely assembled, and has therefore to be magnetized as a single unit after assembly by placing it in the field of a high-flux pulsing magnet. This means that the maximum size of chuck which can be designed in this way is limited by the size of the electromagnet available for this purpose. To some extent this limitation in chuck size can be overcome by ganging a number of chucks end to end on the machine table, but this arrangement has the disadvantage that each unit has to be controlled manually.

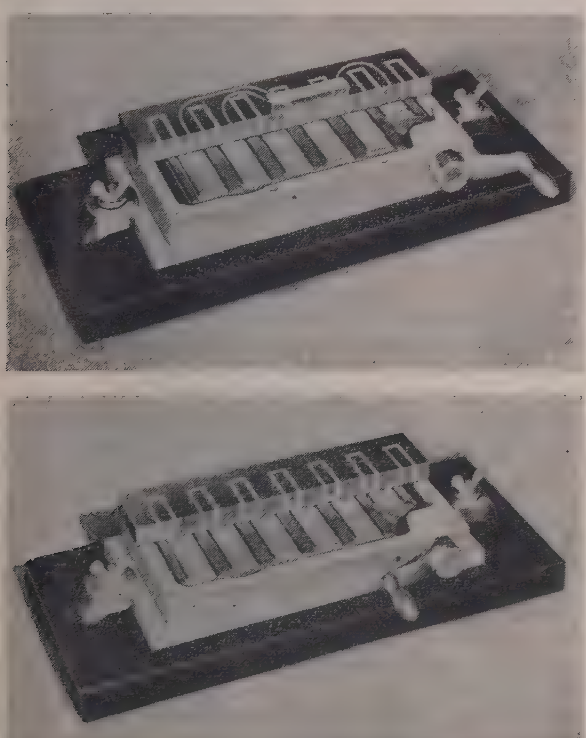

Fig. 2.—Cutaway view of magnet assembly for permanent-magnet chucks.

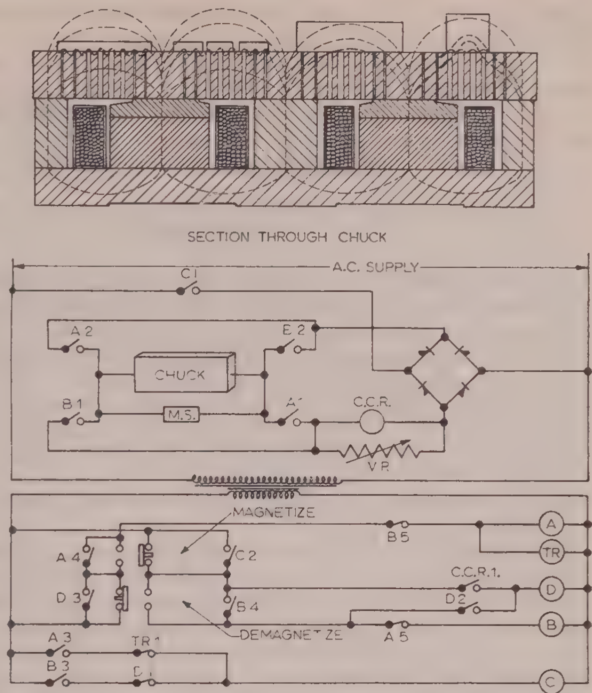

Fig. 3.—Permanent electromagnetic chuck and schematic of control system.

The most recent development in this field is the permanent electromagnetic chuck. Here the workpieces are held on the chuck due to the flux passing through them from permanent magnets, these magnets being magnetized and demagnetized *in situ*, as illustrated in Fig. 3. The permanent magnets are magnetized after the workpiece has been loaded on the chuck by a single short current pulse giving rise to a very high flux density. The remanent magnetism of a permanent-magnet magnetic flux path is, of course, highest if the magnetic path is not broken after excitation, thereby giving the greatest magnetic pull to the workpiece, and this is the principle employed. For demagnetization, a reverse current pulse of fixed magnitude but of adjustable application time is used, facilities being incorporated in the control equipment for easy time adjustment. This demagnetization time naturally varies with the size, shape and magnetic remanence of the workpiece.

This type of chuck is made in single units up to 40 in $\times$ 20 in, and multiple chuck assemblies can be used on large machine tables so that a single pushbutton-operated magnetizing and demagnetizing unit only is required the schematic connections of which are also shown in Fig. 3.

The addition of exciting coils in this type of chuck, although only short-time rated, necessarily increases its total volume, and for any particular active chuck-face dimensions, it is therefore thicker than the equivalent size of permanent-magnet chuck and may limit the height capacity of the machine.

These recent developments will undoubtedly enable greater use to be made of magnetic chucks for holding much larger ferrous workpieces than formerly and avoid the need for many jigs and fixtures. Very heavy cuts on milling, planing and grinding machines can now be taken without risk of movement of the workpiece whilst machining is in progress.

DISCUSSION ON

'A SURVEY OF STREET LIGHTING AND ITS FUTURE'*

Before the NORTH-WESTERN UTILIZATION GROUP *at* MANCHESTER *7th February*, *the* NORTH LANCASHIRE SUB-CENTRE *at* LANCASTER *8th February*, *and the* NORTHERN IRELAND CENTRE *at* BELFAST *14th February*, 1961.

Mr. H. Carpenter (*at Manchester*): The authors rightly stress that efficient main-road street lighting should, easily and quickly, provide correct information for all road users. This requires effective visibility which avoids disability and distraction glare. Street lighting should also serve as a help and guide to motorists, and the authors will agree that installations should, on no account, misguide vehicular traffic by incorrectly positioned lighting units or by forming confused light patterns on the roadway. This is particularly important on wet nights when visibility is restricted and high-brightness streaks and shadows are dangerous.

I am concerned about a recent road-safety campaign advocating the increased use of dipped headlamps. Whilst sympathetic to the views of the Chief Constable of Lancashire that elderly people have difficulty in seeing the small sidelights of modern cars, my feeling is that, if the cars themselves are not clearly visible on our main roads, it is high time that the street lighting was improved. Headlights, even when dipped, are frequently misaligned, and increased usage adds to the hazards of distraction and disability glare often responsible for dangerous situations and accidents. Surely the emphasis should be to spend more money on providing more effective street-lighting installations.

Mr. Waldram's recent paper on motorway lighting emphasized how ineffective and misleading is the information conveyed to the motorist by his own headlights, whereas fixed street lighting helps to produce a constant picture ahead enabling the motorist to position himself accurately and drive safely and properly.

Tubular fluorescent lighting receives little comment by the authors, despite the apparent advantages of this type of installation. Now that street lighting, indeed all electric lighting, is cheap enough for the desired 'quantity' to be easily and readily available, more emphasis should be placed on 'quality'.

Blackpool recently converted several 'intermediate routes' from 125 W mercury-vapour to 120 W tubular fluorescent lighting, with such decided improvement that it attracted favourable public comment. Would the authors express their opinion on whether this was because

(*a*) 'Near white' lighting produces more natural colour rendering, and does not tend to mask colour contrasts, inherent in mercury installations and more pronounced under monochromatic sodium lighting.

(*b*) Efficiency of lantern design, and a linear light source, tends to produce a more diffused light distribution, helping inter-reflection from modern road surfaces, which improves the silhouette effect, particularly on wet nights.

(*c*) The light source is one of low brightness resulting in a relative absence of glare.

(*d*) Light output has been increased and the mounting height raised from 15 to 20 ft?

Similar improvements are noticed when 80 W mercury-vapour installations, of 16 ft mounting height, are altered to 80 W tubular fluorescent, and 400 W mercury-vapour installations, of 25 ft mounting height, are altered to 320 W.

The authors do not mention 'uniformity' in street lighting, which is a topical subject although often misinterpreted by a misguided lay public and frequently advocated without clear indication of what is intended. Uniform levels of lighting on contiguous thoroughfares is desirable, but any question of standardization of type or colour of installation would be detrimental to progress. Frequent changes should not, of course, occur on short lengths of road, and with proper liaison this is avoidable. The newly formed consultative committees should help in resolving problems of this kind, but, in my opinion, complete standardization would impose restrictions and have a stifling effect on design and development. Would not a continuity of light, of one colour and type, be so psychologically boring that that, in itself, would constitute a danger?

Mr. W. E. Ballard (*at Manchester*): I agree with the authors that so often we meet efficient lighting installations giving good revealing power but having a poor daylight appearance. In this respect, whilst tubular fluorescent lamps undoubtedly give excellent results with a minimum of glare, the lanterns which are often coffin-shaped appear ungainly. It has always seemed a pity that our lamp manufacturers have been so far unable to produce U-shaped lamps to enable smaller and neater lanterns to be employed.

There is no doubt that the sodium lamp has triumphed over all other light sources to date, and certainly in the North of England where big change-over schemes have been taking place in such large cities as Manchester and Sheffield.

I cannot altogether agree with the statement in Section 3.1 that broadly the total operating costs for the three main discharge lamp sources, i.e. sodium, colour-modified mercury and tubular fluorescent, are about the same. The initial cost of tubular fluorescent lanterns and equipment is still much greater than in either of the other cases, and this must be reflected in the total running costs, including amortization.

In Section 5 it is stated that if the mounting height of a light source is doubled the average illumination is halved, but surely owing to the square-law rule, the figure should be a quarter.

It would be very useful if the powers-that-be were made aware of the suggestion in Section 6.1 that there is a widely held view that a new Group A installation can be installed and maintained at no cost to the community as a whole since an accident on average costs £700 per person, which is the average cost per mile per annum of Group A lighting. This may or may not be strictly true but it is good propaganda for better lighting.

Reference is made to the 100 ft high special lantern at Munich. I wonder how they manage to get at the lantern and lamps for service and maintenance, as one of the difficulties of these increased mounting heights is the special equipment which becomes necessary.

Reference has been made to the possible lighting of motorways, and I would like to see installations with a mounting height of the order of 35 ft and spacing if possible approaching 200 ft with suitable light sources and lanterns.

* STEVENS, W. R., and FERGUSON, H. M.: Paper No. 3260, May, 1960 (see 108A, p. 127).

Lastly, although not strictly coming under the heading of street lighting, it does seem that there is a vital need for properly lit zebra crossings.

Mr. H. F. Cork (*at Manchester*): Whilst the lack of progress in street lighting is due to financial restrictions, this is not the fault of local authorities, which, on the whole, have every desire to provide better lighting and thus increase road safety. However, a local authority has many calls upon its purse, such as education, health and housing, etc., and all these have high priority and would continue to have for a number of years to come. Therefore the lighting engineer must expect a limited budget, and on this basis he must plan to provide street lighting that would be of benefit to the greater number of residents rather than embark on some of the flamboyant schemes such as those in some Continental towns.

Mention had also been made of the Code of Practice, and whilst it is desirable, and indeed essential, to increase illuminations, the principles of the Code are thoroughly sound and should be adhered to.

As the authors come from London they will no doubt have some information concerning the standardization of lighting throughout the various London boroughs, and if they can give any information on this matter it will be most welcome. The lighting of 'express-ways' is now receiving active consideration in this area, and if this problem had been dealt with in the London area, the experience obtained will be most welcome.

It is interesting that the new type of non-skid road surface appears to affect the efficiency of the sodium installation rather less than either the mercury-vapour or tungsten installations.

Mr. T. L. Robinson (*at Manchester*): The cost of dusk-to-dawn lighting compared with dusk-to-midnight lighting is influenced by two expendable items, namely electrical energy and lamps. The cost of additional hours of operation is not directly but inversely proportional to the shorter period of operation. Energy for street lighting is generally subject to a two-part tariff, so that the demand charge being an annual cost related to the size of lamp is covered by the short-period costs. Any additional hours are subject only to the running charge. The average cost of energy is therefore less for a longer period of running hours. The declared life of discharge lamps is principally related to an assessed number of switching sequences, and hence extended lighting hours associated with one switching operation attract a much lower average lamp-hour cost over the longer period. These two attractive features make it difficult to understand why street-lighting authorities do not more readily avail themselves of the economic advantages of dusk-to-dawn lighting and by so doing minimize the hazards of passage in the hours of darkness. The use of small low-rated fluorescent lamps in street signs and bollards has introduced a change of switching practice, whereby lamps are in continuous 24-hour daily operation, thus eliminating the cost of automatic switching control. The cost of additional energy consumed by this practice is offset by the safety advantage of illumination during periods of premature darkness and fog.

The relatively high starting current associated with mercury discharge lighting has contributed to the economy which has influenced the adoption of sodium lighting on longer traffic routes. The provision of motorway lighting will be influenced by the voltage drop of the special lighting cables which would have to be provided in the absence of normal distribution cables, owing to the geographical isolation of the motorway from suitable means of electricity supply.

Mr. A. Stewart (*at Manchester*): What proportion of the total lighting illustrated in Fig. 7 is derived from the wall lanterns and what proportion is spillage from the shop-window lighting?

Have the authors any comments to make on the lighting of the side roads which have a traffic density lower than main roads but much in excess of the normal side roads, e.g. estate roads used by public transport. As many of these roads now fall between Groups A and B requirements, will the improved standards add to this difficulty?

Many otherwise good installations are adversely affected by vandalism. Is there any hope of a 'boy-proof' fitting?

Mr. J. Tozer (*at Manchester*): In designing the lighting of roads and particularly roundabouts, we must take into consideration the impact strength of lighting columns. I have noticed what seems to be a high rate of destruction of columns at the roundabout on the north end of the motorway M1, where the lighting layout follows a conventional pattern. Surely here is a case for either resiting the columns where they are less vulnerable or providing some sort of crash barrier between each column and the road. The barrier should be designed to slow down a vehicle sufficiently to prevent it wrecking the column. This should have an added advantage in that it would reduce the hazard that the present lighting column offers to modern fast traffic.

Referring to side-street lighting, the authors advocate the illumination of building faces. The methods employed should ensure that the street lamps are not shining into bedrooms, particularly where it is intended to keep the street lighting switched on throughout the night.

Mr. H. Carpenter (*at Lancaster*): Road accidents, in 1959, cost the country £219 million, whereas street lighting costs less than £15 million annually. Good street lighting reduces accidents after dark, particularly in built-up areas, and surely this is sufficient economic justification for increased expenditure. A 30% reduction in personal injury can be expected, and present-day costs, despite monetary changes, represent only about 21s. per annum per household (5d. per week), i.e. less than a box of matches per person. The costs per lumen per annum were approximately ½d. in 1959, 1d. in 1939 and 0·8d. in 1932. Thus comparatively, the costs are less than a quarter of those 30 years ago.

In Section 3.1.2, aesthetics are placed before technical and personal factors, and yet in the sub-Section rating they are next to last in importance. The latter would appear more correct. Technicalities must have priority, however pleasing and important are aesthetics, although compromise is inevitably necessary.

The authors rightly draw attention to the serious problem of controlling glare and the interrelated visibility problem of road-surface patchiness. The fundamentals of Continental and British practice are different, and we know of the Brussels experimental comparison 18 months ago. Glare in British installations should be reduced, and despite economic considerations, a better spacing/height ratio is necessary. With higher-intensity light sources available, and increased mounting height advocated, some engineers are suggesting increased spacing to provide more economic installations. Surely, 'better' lighting should be urged, and with 30–35 ft mounting height, ideal Group A installations at 100–120 ft spacing are possible, i.e. a spacing/height ratio of less than 4 : 1.

Codes of Practice and their influence on types of street lighting, and the present revision, are mentioned. 'Intermediate standard' roads are a problem. Group B could be extended to cater for 13–20 ft mounting height or a new class (between Groups A and B) could be introduced. Is the division between Groups A and B a practical proposition at present? Should not mounting heights be decided by the local engineer (with minima reservations)? Lighting engineers may have appreciated group divisions of lighting but not the motorist.

Are upper limits necessary? Economics arbitrate, and if minima were specified for traffic and other roads, the rest could

be left for local determination. Standards will continue to increase, to cope with progressive lighting demands, and if the cost per lumen continues to decrease, as seems possible, requirements even higher than those now advocated could become feasible and necessary.

'Near white' tubular fluorescent street lighting has many advantages, and I enthusiastically support the plea for more decorative lighting.

More all-night street lighting was advocated in a previous discussion. Lighting authorities incur capital expenditure at about £3000 per mile for main road lighting, and yet the extra operational and maintenance costs (dusk to dawn instead of dusk to midnight) is about £3 per annum, and for side-road lamps, about £1 10s. per annum, i.e. an increased annual budget of 10–15%, or 1s. 9d. per annum per citizen. Surely this is worth while, considering the additional facilities for the police, the added safety and comfort to householders, the advantages of parking without lights and the lessening of early-morning danger from cars parked without lights on unlighted roads.

Mr. W. J. Wright (*at Belfast*): In the Introduction the authors state that the cost of a modern main-road lighting installation, including amortization, power and maintenance, is about 1d./ft^2 per annum. In the few checks I have made the figure came out at rather more than 1d.

I am very perturbed at the very dismal and costly picture the authors paint regarding the colour of the dark non-skid road surfaces now being installed. In view of the importance of obtaining a suitable road surface from the street-lighting point of view, and the economy which could be effected by obtaining a compromise between a non-skid and a slightly brighter surface, would it not pay to spend much more money on research into this important matter?

Regarding the selection of lanterns from the three types available (Section 3.1.1), it has been the practice in Belfast to use the medium-angle beam, the only exception being where cut-off lanterns are used on a newly constructed dual-carriageway road adjacent to an airfield. For the standard mounting height of 25 ft the difference between the 80° high-angle and 75° medium-angle beam would affect some 50 ft of road surface at a distance of 150 ft from the lanterns and only 25 ft between the 75° and 70° cut-off beam. In other words, the discomfort glare from the high-angle beam is twice that from the medium-angle beam.

I agree with the authors that, for good street lighting, the spacing/height ratio must be reduced. In Belfast a large mileage of roads is lighted by erecting lanterns at a height of 25 ft on trolleybus standards, 105 ft apart, giving a ratio of approximately 4 : 1. The result is very good street lighting.

The disadvantage of this type of installation lies in the fact that the lantern positions are determined by the positions of the trolleybus poles.

It is difficult to agree with the authors that colour is of little importance to a driver owing to the low brightness of a street-lighting installation (Section 3.1.2.5). When inspecting a recently-commissioned sodium installation I noticed that the red plates of 'No Entry' traffic signs were virtually undistinguishable under the light, the signs being recognized mainly by shape. Also, under sodium lighting the grass verges were not clearly defined for the motorists.

I agree with the authors' comments on side-street installations. Can they give their recommendations for the treatment of bends on Class B routes? I suggest that an increase in the mounting height should be permitted in the revised Code of Practice to permit overhanging lanterns to be erected at the kerbside without obstruction to large vehicles such as buses.

I would like to know whether similar lanterns and similar shaped lamps were used when carrying out the comparative tests between sodium and mercury lighting to determine the 1·7 factor.

The description of the experimental installation in Munich is very interesting. If lamps are to be mounted at this height, it follows that steeplejacks become an essential part of the maintenance staff. I have seen a xenon light source and was very much impressed with the colour rendering. Is there a possibility of xenon being used as future light source for general street-lighting work?

Major R. E. Jones (*at Belfast*): In Section 4 the authors refer to the admitted success of the fluorescent lantern, in spite of its inherently low coefficient of utilization.

The fluorescent lantern has been remarkably successful in Northern Ireland. In 1950 the Board commissioned the first fluorescent street-lighting scheme in Northern Ireland, for the Lisburn Urban District Council, and this installation of 167 Group A lanterns was then the largest fluorescent street-lighting installation in the world, i.e. to be carried out in one contract.

At present there are four lighting authorities in the Board's area of supply with exclusively fluorescent street lighting. One was changed over from gas, one was changed over from a combination of gas and metal filament, and the other two installations were converted from a combination of mercury vapour and metal filament.

Fluorescent lanterns account for 26·7% of the total street lighting in the Board's area, and the present indications are that this will increase to, say, 50% in the next ten years.

The remaining light sources in the Board's area of supply are as follows:

Metal filament	64·6%
Mercury vapour	8·5%
Sodium	0·2%

It is a common experience to find better street lighting in the small towns and villages of Northern Ireland than in some of the London boroughs. I recently drove from Waterloo Station to London Airport, and I could not help contrasting the curious assortment of street lighting—gas, mercury vapour, sodium, metal filament and fluorescent. It seemed an extraordinary arrangement, most confusing to the motorist, and not one of these installations was as good as, say, Warrenpoint in County Down, a small seaside town of less than 3000 inhabitants.

Driving the equivalent distance in Northern Ireland from Balmoral through Belfast along York Street to Newtownabbey, Greenisland and Carrickfergus, say 14 miles, the motorist has fluorescent lighting the whole way, through the areas of four different lighting authorities—two borough councils, one urban council and one rural council.

This desirable treatment was not obtained by a co-ordinating committee, but rather by the large authority following the excellent example of its smaller neighbours.

Mr. W. Szwander (*at Belfast*): Good street lighting, apart from satisfying economic requirements, must serve adequately its main purpose of providing sufficient illumination for the users of the streets, at the same time complying with certain aesthetic standards—in other words creating a pleasant appearance. The application of the above criteria obviously leads to a differentiation between streets (or roads) outside built-up areas, where almost the only user is the car driver and the aesthetic aspect hardly needs to be considered, and on the other hand the streets in built-up areas (whether residential or business and shopping centres) in which latter cases the aesthetic considerations become not less important than those of actual satisfactory illumination. The pedestrians and car drivers after they have stepped out of their cars represent here the vast majority of the road users, and their aesthetic requirements cannot be disregarded or

sacrificed for better illumination standards (or better economics) to be achieved at their expense. Thus in built-up areas the colour aspect of lighting becomes one of the most important considerations, and metal-filament or fluorescent lighting scores heavily in that respect over monochromatic mercury-vapour or sodium sources of light. The latter particularly are most objectionable in places where one has to dwell any length of time, and whatever may be their other advantages, they should be completely ruled out in built-up areas.

While financial limitations in most cases preclude expenditure aimed solely at the provision of aesthetic effects, no matter how much it might be desirable, yet much can be achieved through endeavours to improve the actual standards of illumination by ways which at the same time contribute to the enhancement of aesthetics. Increased suspension height of the light sources not only permits reduction of the number of lamp columns, which are always objectionable from the aesthetic viewpoint, but also contributes to the general pleasant appearance of, say, a shopping street, through illumination of the house fronts, thus creating an impression of filling the space with light. Wall mounting of lamps is a line of development worthy of much more attention than heretofore, in view of the complete elimination of all supporting columns. Certain developments, which are occasionally unavoidable through local circumstances, can be very objectionable from the aesthetic viewpoint; for example, the use of trolleybus poles resulting in lamps not being located at uniform heights and along even lines, or the use of overhead wires for connecting the lamps.

The large dimensions of lanterns for fluorescent lamps are ugly in daytime, and ways of overcoming that objection are well worth seeking. The wall-mounting of such fittings parallel to the street axis would be one of the possible solutions.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. W. R. Stevens and H. M. Ferguson (*in reply*): Mr. Carpenter makes the point that street lighting should be adequate to obviate the need for headlights, whether considered from the point of view of the motorist or the pedestrian. This has always been the aim in main-road lighting, and if it has not yet been achieved, it is high time that the levels of lighting were raised sufficiently to meet this need. The advent of non-skid road surfaces with their relatively poor reflection characteristics adds emphasis to the point. In the majority of side streets, however, it will probably be uneconomic for many years to provide sufficient light to enable motorists to proceed safely without their headlights.

He also gives some very interesting details of improvements in the lighting of 'intermediate routes'. There is little doubt that all the factors listed are responsible for the improvement—the increased mounting height with more light, the improved colour and lower source brightness. In addition, a significant improvement has been achieved by the increased quantity of light falling on the faces of the buildings—a factor which we regard as very important in built-up areas. The objection, raised by Mr. Tozer, of excessive light shining into bedrooms, can be largely obviated by careful design of the lanterns used in residential areas.

The problem of 'intermediate routes' generally is raised by Messrs. Carpenter and Stewart. It seems likely that the new Code of Practice for street lighting will go a long way to meet these cases which have no legitimate place in the present Code. In addition, it should largely meet the criticism that upper limits of mounting height should be left to the discretion of the local authority, with minimum values stated.

Several speakers comment on the aesthetics of street-lighting installations. Mr. Ballard criticizes the appearance of tubular fluorescent lanterns, and Mr. Szwander would completely rule out the use of mercury and sodium sources in built-up areas. We have much sympathy with these points of view, particularly the latter, but not everybody would agree. Most of us are agreed that we should put the lighting requirements before aesthetic considerations, but surely the time has now come when the technical requirements can be met so cheaply that we should be able to pay attention to the appearance of an installation as well as its performance. An individual fluorescent lantern mounted on a tall column and tilted up a few degrees from the horizontal can look very well in isolation, but an installation of such lanterns in a winding road with the occasional roundabout can be disastrous. Perhaps Mr. Szwander's suggestion for the more extensive use of wall-mounted lanterns with their axes parallel to the road should be given more serious consideration. Perhaps, too, we should now put more emphasis on good colour, particularly for built-up areas, rather than on efficiency, which, until now, has largely dictated progress.

Mr. Ballard declares that there is no doubt that the sodium lamp has triumphed over all other light sources to date. Major Jones, on the other hand, tells us that sodium lamps account for only $0{\cdot}2\%$ of the lighting in his area. Perhaps one of the fascinations of public lighting is that we are never likely to be unanimous in these matters of taste. Nevertheless, we have to agree (with a tinge of regret) that London and many other large cities could learn a lot about street lighting from Belfast.

Mr. Ballard comments that tubular fluorescent installations must be more expensive overall than others because of the relatively high initial cost of the lanterns. In general, the difference is quite small because the lamps themselves are cheaper and more efficient than others. We agree with his desire to see higher mounting, but this should not be coupled with a proportionate increase in spacing. We must reduce the spacing/height ratio if we are to deal successfully with modern road surfaces. Mr. Cork's suggestion that sodium lighting is less seriously affected by these surfaces than other sources may be true, since sodium lighting is generally less glaring than others and the difference may become more marked as the road brightness falls. There is also some evidence to suggest that sodium lighting generally produces less patchiness than other sources; again the difference may be more noticeable as the roads become rougher.

Mr. Wright refers to the dismal and costly picture which we have painted regarding the dark non-skid surfaces. Fortunately these new surfaces are not yet in the majority, although they are likely to increase in the future. We have no time to lose in redesigning our installations to deal with them. We need a smaller spacing/height ratio, more light and better control of the light to mitigate glare: none of these is technically difficult to achieve and the cost need not be excessive. Judged by present indications, there is little chance of finding road-surface materials which are good from the point of view both of street lighting and skid resistance at an economic price.

We could all wish that the calculations of discomfort glare as between high-angle- and medium-angle-beam lighting were as simple as Mr. Wright suggests. Nevertheless, we wholeheartedly agree that the tubular fluorescent installations in Belfast with a spacing/height ratio of 4 : 1 (opposite mounted) are very good.

DISCUSSION ON 'SUBMERSIBLE PUMPING PLANT'*

Before a Joint Meeting of the NORTH-WESTERN CENTRE *and the* MERSEY AND NORTH WALES CENTRE *at* MANCHESTER *8th November, and the* SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH *29th November*, 1960.

Mr. W. E. R. McCarter (*at Manchester*): Reference to records of more than 20 years ago of borehole pumps driven by surface motors shows that efficiencies of at least 80% could be obtained on the larger pumps of low specific speed fitted with removable diffusers. The medium-specific-speed pumps with fixed diffuser vanes showed much lower efficiencies at that time, possibly owing to lack of experience in the design of mixed-flow impeller vanes. From Fig. 3 it is evident that the authors are able to get a good efficiency, of 80%, at both low and medium specific speeds from the submersible type of unit described. Fig. 3 brings out clearly the tendency of low-specific-speed pumps to have a continuously rising power curve. This awkward characteristic can be overcome by increasing the number of stages (and therefore the specific speed) for a given duty, but any device adopted to produce a non-overloading power curve, without increasing the number of stages, would cause a substantial reduction of efficiency.

In Section 17.1.1 the authors state that all sizes of pumps of the same specific speed have the same efficiency provided that the output is the same, and experimental evidence is shown in Fig. 17. This view, however, is not shared by all designers, some of whom use the Moody index of 1/5, or an even greater index, to denote a gain of efficiency with size. The authors' views are therefore a warning that care is required in making claims for the efficiency of a commercial pump based on a smaller model.

It is stated that a stainless-steel shaft running in bushes of carbon, plastic or rubber has been found to be satisfactory. My experience of water-lubricated bearings, not necessarily for this particular application, has indicated that bronze white-metal bearing bushes are more satisfactory: these materials would not be any worse from the point of view of circulating currents than carbon bushes.

On the subject of thrust bearings, it is said that a change from carbon to white-metal tilting pads gives an improvement as regards losses in the motor. Has this change been good from the point of view of the life of bearings?

A carbon shaft seal is fitted at the driving end of the motor top bearing to prevent entry of grit and contaminated water, and of course an expansion chamber with rubber diaphragm is fitted at the bottom end. Do the authors feel that this carbon ring is really necessary, since, with a fairly long bronze bush, damage by a small amount of contaminated water would be so small as to be negligible?

On the smaller machines limitations of cost and space are important and may well be a limiting factor, but on the larger sizes has it been considered whether forced circulation of water is desirable from the point of view of effective bearing lubrication, possibly through a hollow shaft?

I agree that the type of winding described is ideal for this purpose. However, have the authors had any experience of coverings other than p.v.c., such as high-density polythene?

There seem to be disadvantages in winding each phase with a single length of wire. While I agree that it is desirable to keep the number of joints to a minimum, with present materials and techniques there would be no disadvantages in jointing each coil as with a normal dry machine. So far as I know the melting-polythene technique appears to be quite satisfactory as do self-adhesive and self-bonding polythenes.

I am particularly interested in the authors' remarks on the effect of rotor stampings and bars in increasing shaft rigidity. On conventional machines it is my experience that these have very little effect and calculations for critical speed, ignoring the effect of the stamping, have shown considerable accuracy, although rarely exact.

Mr. H. E. Clapham (*at Edinburgh*): Many centrifugal pumps have a rising horse-power characteristic and often operate at less than the designed head. Under these circumstances, unintelligent or careless operation can easily lead to motor overloading, unless the motor rating has been made sufficiently liberal to cover the risk. In this respect, close collaboration between pump and motor designers is most valuable, especially as most present-day motors are continuously maximum rated and therefore not designed to carry any sustained overload.

In Section 10.3, 3·3 kV windings are mentioned. Although the use of this voltage may reduce the weight of the supply cable, it will probably increase the size of the motor. What is the lowest horsepower rating advisable for 3·3 kV submersible motors, and are there any circumstances where the authors would recommend the use of high-voltage submersible motors?

Is there a risk of the pumpset swinging in the borehole owing to suction effects and so causing damage to itself or the borehole?

In at least one installation quite a lot of sand is entrained with the water, causing rapid wear in the pump and the possibility of the borehole collapsing. The disturbance created by starting and stopping appears to be mainly responsible for dislodging sand in the borehole, for if pumping is carried out continuously the amount of entrained sand falls considerably. To try and overcome this trouble a variable-frequency supply is being provided so that controlled, very gradual starting and stopping of the pumpset may be possible with a view to reducing the disturbance of the water in the borehole. In order to reduce the number of stops and starts it is proposed to use the variable-frequency supply to control the pump speed, and therefore the amount of water delivered. With this in view a new pump is being installed, having a stable head/quantity characteristic over its full range.

When operating at reduced flow it is seen in Fig. 6 that the motor thrust-bearing load is greater than at rated flow. Is this bearing normally designed to carry continuously the heavier thrust of no-flow conditions? Further, it appears necessary to fix the minimum flow at a value sufficient to provide adequate cooling water for the removal of losses from the pump and motor without undue temperature rise.

It is hoped that the additional expense of the variable-frequency supply will be more than covered by the savings on maintenance on the pumping plant. Have the authors had experience of installations using variable frequency in this manner?

Mr. V. P. Mackay (*at Edinburgh*): I hope that other manu-

* ANDERSON, H. H., and CRAWFORD, W. G.: Paper No. 3147 U, November, 1959 (see 107 A, p. 127).

facturers will pay attention to the recommendations of the authors that the wound stator be immersed in water for one week prior to being built into the pump unit.

The authors recommend pressure testing of the stator winding at the end of the immersion period and while still immersed at 1·5kV. Why has a value of 1·5kV been used? What is the duration of this pressure test, and at what voltage and for how long do they pressure test the stator winding at the end of works test?

What is the opinion of the authors on the use of t.r.s.-covered copper in the stator winding? Have they experienced decentralization of the copper in p.v.c.-covered copper conductors?

Do the authors recommend the immersion of the stator-winding conductors in water prior to winding, and if so for what duration of time and what tests should be carried out?

Most manufacturers position metallic guide bearings within the overhang of the stator end windings and maintain that they never experience trouble due to circulating currents between the bearings and the shaft. Such, however, is not always experienced in practice and in my opinion the authors' use of carbon bushes is the answer to this problem.

It is now becoming quite usual to use submersible pumping units horizontally as boosters in public supply water mains. What modifications, if any, are required on standard vertical units to enable them to be operated horizontally?

Regarding the effect of particles of sand, etc., in the water being pumped, my experience has been of a submersible pump which has been pumping what is known as 'caprous' water. Such water is the colour of yellow ochre. This pump has lead-bronze impellers and was originally fitted with renewable lead-bronze neck rings. After an initial 1500 hours' running the pump was withdrawn for inspection and grooving was found on impeller shoulders and neck rings. On the recommendation of the pump makers new impellers with rubber neck rings were fitted. After 4700 hours' running (equivalent to 154 days continuous operation) the output from the pump had dropped from 560 to 460 g.p.m., a reduction of 18%. The pump was withdrawn and stripped down. Examination showed that the grooving on the impeller shoulders was very much worse than when fitted with bronze neck rings, being 0·0625 in deep. The impellers must again be renewed, which is an expensive matter, even when neglecting the labour charges involved in removing and dismantling the pump coupled with the irritation associated with the pump outage. Can the authors recommend the use of a hard metal, such as stainless or some other steel, on the impeller shoulders and as neck rings to overcome this recurrent trouble?

Messrs. H. H. Anderson and **W. G. Crawford** (*in reply*): Mr. McCarter suggests that the rising horsepower curve of Fig. 3 cannot be changed to a non-overloading power curve at the same number of stages without substantial reduction of efficiency. It is our experience that by modification of area ratio between impeller and casing, a non-overloading power curve can be produced with an efficiency reduction which is sufficiently small to be economic on duties where large head variations occur. Gentle swinging of the pumpset and rising main in the borehole or well may sometimes occur, but we have not known this to have any harmful consequences or to demand any special anchoring, which, in general, is impracticable.

The thrust bearings are normally designed to carry continuously the heavier thrust of no-flow conditions. In general, submersible pumps, unlike boiler feed pumps, never run continuously at very small or zero flow, and therefore the provision of a leak-off valve to avoid overheating is unnecessary.

The use of a variable frequency for the purpose of avoiding disturbance of sand in the well when starting and stopping the pump is very rare indeed. Even for variation of duty, a variable frequency or variable voltage is very rarely used since the normal characteristic of the submersible pumps shows a very large head variation with little efficiency variation.

In cases of handling severely abrasive water, harder materials, e.g. the various stainless steels, could be used, and in the limit, stellite could be deposited upon the clearance surfaces of the impeller neck rings, bushes, etc., but this latter material is extremely expensive.

We have used carbon guide bearings and stainless-steel shafts in submersible motors for many years and have never had a failure which could be attributed to electrolytic action. We are aware that many other materials are available, but we do not think it advisable to change to any of them because we have heard of a few cases of bearing failures which have been attributed to electrolytic action when using metallic bearing bushes. The life of the thrust bearing is rarely a limiting feature in the operating life of these motors and the change to white-metal-lined pads has not altered this condition.

Various insulating materials have been used as a covering for the stator-winding wire. Rubber was the first material to be used but was discarded immediately polyvinyl chloride (p.v.c.) became commercially available. Polythene was also tried but gave trouble with cracking. Stress and corrosion cracking of polythene is now much better understood, and now that irradiated polythene is commercially available the use of polythene as a wire covering is being re-examined. A number of years ago we did immerse the p.v.c.-covered wire in water for some time before using. The covering is, however, now of such consistently high quality that we find this is unnecessary, so that all we do nowadays is to immerse the coil in water and flash immediately at 4kV. The flash test on the finished winding is limited to 1·5kV for one minute because the previous flash test has shown that the insulation is perfectly satisfactory and it is only now necessary to check that no mechanical damage has been done to the winding and that the taped joints are mechanically sound. With present techniques the joints in the winding are perfectly sound; however, the more joints there are the greater is the probability of an unsound joint, and we therefore prefer the pull-through winding for a wet-type submersible motor. The lowest horsepower rating for 3·3kV motors is 200/250hp. High-voltage submersible motors for this and larger outputs show a distinct advantage over low-voltage motors when the installations are deep.

We agree that in conventional machines the rotor bars and stampings have little effect on the critical speed, but we have made careful measurements of the deflections of submersible-motor rotors and found that it is necessary to allow for the stiffening effect of the rotor bars to bring the calculations and observations into line with each other. This is a very good example of the fact that the approximations made in design are only valid as long as the design follows the conventional pattern; with any distinct change from the conventional pattern the approximations must be re-examined.

Most of our submersible pumping units are suitable for horizontal running. It is our experience that some form of shaft seal is really necessary to ensure a long operating life; however, it may well be possible to simplify the design. Our experience so far has been that forced circulation of the water inside the machine is not worth while. We do, however, encourage the natural circulation in the thrust bearings because this can be done without undue difficulty or expense.

DISCUSSION ON

'MEASURED AND ELECTRICAL-MODEL CHARACTERISTICS OF BUILDINGS HEATED BY FLOOR THERMAL STORAGE'*

Mr. R. B. Rowson (*communicated*): In view of the importance of the control of off-peak heating installations to secure economical operation, it is disappointing that the only reference appears to be the very vague statement in Section 2.2. Could the authors elaborate on how they decided the switch-on times on the basis of late evening temperatures?

The elaborate measuring equipment installed might have led one to expect that more results of measurements on the building rather than on the analogue would be given. Even such pedestrian figures as the calculated heat loss of the building, annual consumption and degree-days—or summation of inside–outside temperature differences—would have been helpful. After all, it is well established that an electrical network can be used as an analogue of a thermal system—the problem is to decide what values to put into it.

As regards measurements, I am puzzled by the $\frac{3}{4}$in thick thermocouple plates mentioned in Section 2.1(*a*). It would be useful to have details of their performance, particularly as compared with the thinner but still relatively thick plates (*b*).

Fig. 4 is very interesting and it would have been useful to include annual figures in respect of covered unheated ground. Such figures are not, I think, generally available, except for the summer months, and it would have been useful to complete the series.

Owing to the high proportion of heat supplied by lights, machines and operatives, it is perhaps relatively easy to obtain good results in the factory described. Even so, excessive ventilation rates can have a noticeable effect and are difficult to avoid in a factory building. Have any practical methods of reducing ventilation loss been devised?

The heat flow coefficients in Fig. 10(*a*) are low even at their maxima and may illustrate the danger of heat flow on the difference of floor-surface and air temperatures. Possibly in this building the air temperature was higher than a.u.s.t., or there may be a 'size' effect, as there is in the case of the downward losses. The tests on which the more usually accepted figure of $1 \cdot 6$ Btu/h-ft^2 per degF (and higher in the United States) was based were on relatively small slabs, and it would be useful to know if Fig. 10 is based on the whole or a small part of the floor.

Messrs. E. D. Taylor, B. Berger and G. Blaylock (*in reply*): The factory is controlled by a number of simple inside on-off thermostats linked with an outside thermostat—a system well suited to 24 hours a day occupation. We would not necessarily adopt the same system were the building occupied for a shorter time. During the period between the completion of the building and the time when heating was needed, we measured the characteristics of the building, knowing the daily energy input and the inside-outside temperature difference. This was sufficient to gauge the input for heating during the first week, and this additional information provided the data for a straight-line graph showing required hours of heating against outside temperature. The latter was read at 10 p.m. and the heating switched on then for the required time. Later, when the weather became colder, the heating was put on at 6 p.m. This system worked satisfactorily for several months until the thermostats were installed. We agree that for intermittent occupation there will be a most economical operation and suggest that this is the very type of problem that the analogue solves.

The paper is intended to make the point that, despite careful metering, it can make no suggestion for more correct U-factors. The design data themselves and on the analogue using the published constants, forecast the performance as accurately as the data are known. We refrained deliberately from publishing values such as annual heating consumption, which can be misleading unless qualified in detail. The statements on U-factors and efficiency should be sufficient in themselves for most purposes, though the other data are available.

We considered thermocouple attached to metal as giving the most reliable readings; a thickness of $\frac{3}{4}$in gave robustness and a distance small compared with temperature gradients. This is clearly untrue for the upper three or four discs and hence the shorter probes had thin discs.

Unfortunately no suitable enclosed but unheated building was available for measurement, and we agree that such a measurement would have given interesting information on the thermal impedance of the building.

In a large factory building with natural ventilation it is difficult to be precise about ventilation; a direct measurement on the diffusion of a radioactive tracer would probably be necessary. In this particular case it was impractical to clear the whole building for the necessary time and the resulting measurement would have had little meaning since the air change rate was much affected by the utilization of the large doors. The floor heating system itself was an important means of reducing excessive ventilation heat losses by the elimination of the strong convection systems associated with localized heating. This is demonstrated by the uniformity of the air temperature from floor to crane height mentioned in the paper.

Convection heat transfer upwards from large horizontal surfaces is discussed by Danter in Reference 12, where he gives a correction to the heat transfer coefficient for the 'equivalent diameter' of the surface, but it is doubtful if this can be extrapolated to the large size of floor in the factory. The measurements on which the heat transfer coefficients of Fig. 10 were based were made on a small group of operating heating mats, so that the air temperature and surrounding structure temperatures should have been effectively independent of the heat input.

* Taylor, E. D., Berger, B., and Blaylock, G.: Paper No. 3532 U, June, 1961 (see **108** A, p. 226).

DISCUSSION ON

'SOME CONSIDERATIONS IN THE APPLICATION OF POWER RECTIFIERS AND CONVERTORS'*

Before the SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP *at* BIRMINGHAM 14*th November*, 1960, *and the* NORTH STAFFORDSHIRE SUB-CENTRE *at* STAFFORD 16*th January*, 1961.

Mr. J. Terry (*at Birmingham*): Those who have been associated with the installation and operation of large variable-speed rectifier-fed d.c. machines will undoubtedly have run into the harmonic problem. Plant that is installed in a residential area will very quickly come under criticism if its operation interferes with television reception and high-fidelity radio receivers. The publication of Fig. 2 will give the user some idea of the problem, but it would be more helpful if the Electricity Council were to make available, to interested users, the report from which Fig. 2 was extracted. Although the curves included in Fig. 2 relate to recommended practice, with a very persuasive Area Board they invariably become an essential, particularly in view of the consumer's obligations under Section 27, Electric Lighting Act, 1899. Close examination of the curves will show the limitations they impose on the permissible rectifier capacity.

With 6-phase plant on a system short-circuit of 20 MVA the consumer is entitled to 100 kW of rectifier plant. 20 MVA represents a system capacity of about 1 500 kVA, so that the consumer's quota on this basis is something less than 7%. At 12-phase it would be 400 kVA or 27%. With a short-circuit level of 250 MVA the system capacity could be approximately 20 MVA, so that at 12-phase the quota would be something less than 5 MW and at 24-phase something under 10 MW.

If grid control is a permanent feature of the drive, the author suggests a figure of 50–85% of the value quota. This could be embarrassing where a number of potential users of rectifiers had the same point of common connection. In an integrated plant the variable-speed content of the total drive horsepower could easily exceed 50%, and it could well happen that if rectifiers are employed the Electricity Board might find it necessary to lift the fault level at the consumer's terminals—presumably at the latter's expense. Alternatively the consumer might choose to employ the more expensive rotating machines to secure a variable voltage supply.

The introduction of the newer types of rectifier could well extend employment of the variable-speed drive in industry, but not if it is going to bring with it a trail of difficulties. Can the author suggest methods other than phase multiplication for the resolution of the harmonic problem? I have in mind an installation that could consist of a number of variable-speed drives in ratings of 100–400 hp where the semiconductor rectifier might well be suitable.

The power factor of the rectifier is given in Section 4 as 0·95–0·97 maximum, with a lower figure for grid-controlled mercury-arc and semiconductor rectifiers.

In some installations of which I have knowledge, the power factor is around 0·9–0·93: the author states in Section 4 that capacitors may be used for p.f. correction provided that suitable precautions are taken to avoid resonance. Would the capacitors include a series inductance to block the harmonic currents? However, in practice, I have found a certain reluctance on the part of the capacitor manufacturers to deal with this problem. Could the author expand on the information he gives?

Mr. J. D. McColl (*at Stafford*): A great step forward has been taken in this country in the last three years. It has been demonstrated to potential users that the performance of the conventional Ward Leonard system could be duplicated, and in some aspects improved upon, by mercury-arc convertor drives, so that today we have in service units as large as 9000 hp.

The continuous development of the sealed-tank mercury-arc convertor has brought it to a state of reliability which is readily acceptable to modern users. The difficulties of harmonic generation are being met jointly by the supply authority and the application engineer.

Semiconductors have progressed equally. Germanium and later silicon power rectifiers have been widely installed, benefiting no doubt from the general easier acceptance by users of convertor plant, and so far seem to have justified the confidence placed in them. There is no long-life evidence yet available. Whilst relative merits are still debatable, the trend is more towards silicon even for some very-low-voltage applications, the attraction being the smaller package for a given power and temperature. All future electrochemical supplies will be with semiconductors. Power convertors on traction vehicles are now commonplace.

The next big step forward will be the application of the silicon triode; the economic barrier is already lowering. Could the author give his view as to when the controlled semiconductor will begin to supercede the mercury arc for a convertor drive of, say, 1 000 hp?

Could the author explain his understanding of the mechanism of failure implied by the statement in Section 8.3.1 that maloperation of control grids resulting in break-through is liable to occur at vessel temperatures below 15° C?

I would also appreciate an elaboration of the statement in Section 2.2 that the commutating ability of the rectifier rather than its thermal capacity is often a limiting feature.

The paper collates the large number of factors to be considered in the choice of the correct equipment for any given application. What is the author's opinion on the use of a computer to determine the optimum choice?

Mr. N. L. Potter (*at Stafford*): In Section 8·1 the author states that there is a current, voltage and temperature limit for any type of rectifier. This statement I feel is misleading, as for any given design there is a definite vapour-pressure limit for operation at a given voltage. This vapour pressure can be reached by a large variation of current and temperature conditions, and therefore it is not true to say that there is a current and a temperature limit.

It is fairly general practice on the Continent to use short-circuiting devices to protect semiconductor rectifiers, but they have not been used to any extent in this country. Would the author comment on this?

In Section 12 the author advocates the use of air-to-water heat exchangers for cooling semiconductor rectifiers, but he makes no reference as to whether they should be used with raw water or not. Experience has shown that with most industrial plant it is essential to use closed-circuit water to get full reliability.

* McBREEN, J. P.: Paper No. 3215 U, February, 1960 (see 107 A, p. 445).

This in a lot of cases then rules out water cooling on economic grounds.

Mr. P. A. Burdett (*at Stafford*): We have recently completed the investigation and design of an inverse over-current relay for class 3 traction mercury-arc-rectifier protection. The curve approximates to $I^8 t = K$, i.e. 90 min to trip at 1·5 times full load, 60 sec at 3 times full load and 150 ms at 3·5 times full load. Would the author comment on the suitability of this curve for modern mercury-arc rectifiers and suggest requirements for germanium and silicon-rectifier protection?

Mr. J. P. McBreen (*in reply*): For convenience replies have been grouped under subject headings.

Harmonics.—Limitation of harmonics in the supply makes it necessary at present to use a higher number of phases in this country than is usual abroad; in the case of large rectifier-controlled d.c. drives, however, once a 12-phase system is adopted, limitation of voltage fluctuation in the supply is usually the controlling feature in determining the supply rating for a particular drive.*

With the rapidly growing size of supply systems both these limitations will become less important. The use of semi-conductor rectifiers for ratings of 100–400 hp would ease the harmonic problem only if grouped to give an overall increase in the number of phases.

Power-Factor Correction.—In using capacitors for power-factor correction a study has to be made of the supply network, and it is probable that some inductance would be necessary to prevent resonance.

Silicon Controlled Rectifiers for Large Powers.—As larger rated silicon controlled rectifier cells become available, silicon controlled rectifiers will be used more and more for auxiliary drives for which small mercury-arc rectifiers are often used at present. For larger ratings, above say a few hundred horse-power, where the series and parallel operation of cells present both technical and economic difficulties, the grid-controlled mercury-arc rectifier is likely to remain supreme for a considerable time to come, and perhaps indefinitely.

* McBreen, J. P.: 'Power Rectifiers for Industry and Traction', *A.E.I. Engineering*, June, 1961, **1**, p. 243.

Commutating/Thermal Rating Limits.—For various rectifier-controlled d.c. drives, such as those encountered in rolling-mill practice, operating peaks of several times full load may be encountered, often at voltages reduced to near zero by grid control, and the ability of the rectifier to commutate these high current peaks, not thermal limitations, often decides the size of rectifier to use.

Low-Temperature Limit of Mercury-Arc Rectifiers.—When the duty on the rectifier is severe, the low-temperature limit becomes more important, and it is necessary in addition to ensure that the temperature of the space surrounding the anodes and the grids is higher than that of the main condensing zone, otherwise backfires due to mercury droplets, or break-through due to spurious peaks on the control grids, are liable to occur. The latter are also affected to some extent by the design of the grid firing circuit employed.

Use of Computers.—These may offer advantages in determining limiting design features, but I doubt if they will be of any advantage in the selection of type of equipment to use.

Use of Short-Circuiting Devices for Protection of Semiconductor Rectifiers.—A short-circuiter is itself a complicated device liable to fault, and while its use permits a smaller fault-limiting reactance to be used, and therefore a smaller regulation to be achieved, most British manufacturers prefer the simpler arrangement of the additional reactance and h.r.c. fuses for short-circuit protection.

Use of Water Cooling for Semiconductor Rectifiers.—The use of air-to-water heat exchangers with semiconductor rectifiers is advocated only for the small isolated rectifier in a very dirty or corrosive atmosphere. For most rectifiers air cooling is preferable.

Special Inverse-Time/Over-Current Relay.—A special relay of the type suggested would be justified only if its cost was comparable with that of the existing relays it would replace. A B.S.I. committee is preparing a standard for semiconductor rectifiers and, no doubt, they will include recommended rating classes from which the requirements for a similar relay for use with germanium and silicon rectifiers may be obtained.

DISCUSSION ON
'THE SHIELDING OF OVERHEAD LINES AGAINST LIGHTNING'*

Before the North Staffordshire Sub-Centre *at* Stafford *17th October*, 1960, *and the* Western Supply Group *at* Bristol *16th January*, 1961.

Mr. W. P. Williams (*at Stafford*): Although the use of a shielding angle of 45° is commonly accepted, there is a new concept in the paper of its being a limiting or critical angle. From a study of the lightning outages against shielding angle of over 100 transmission lines, very little evidence can be obtained to support this limiting-angle concept. Has the author considered carrying out a detailed study of a particular system in an attempt to discriminate between outages caused by shielding failures and those due to other effects, and so produce some direct evidence?

In the paper a basic assumption is made that the leader channel has a uniform charge along its length. In a recent paper† a new theory was put forward which postulates that the head of the leader channel contains a disproportionately large charge compared with a similar length of the leader proper. The author's views on this theory and its effect on his own reasoning would be interesting.

* Gridley, J. H.: Paper No. 3172 S, January, 1960 (see **107** A, p. 325).
† Griscom, S. B.: 'The Prestrike Theory and Other Effects in the Lightning Stroke', *Transactions of the American I.E.E.*, 1958, **77**, Part III, p. 919.

Mr. W. H. Campbell (*at Bristol*): The importance of shielding overhead transmission lines against lightning can hardly be over-emphasized. In the South Western Division of the Generating Board about 48% of all 132 kV system faults over the six years 1954–59 have been directly attributable to lightning.

In view of the difficulties of simulating conditions in the laboratory due principally to the impracticability of scaling down the dielectric characteristics, it would seem desirable to establish some regular system of trained observation in the field, even in this country.

With regard to the development of bound charges on the phase conductor and earth wire, I would like some amplification of the final paragraph of Section 2.1. Irrespective of the simultaneous

formation of corona on both phase and earth wires, under conditions of equal charge consequent upon their being placed on an equipotential of a leader channel, I would have expected the smaller wire to develop an upward streamer earlier than the larger one because of its higher surface electric force. The effective ratio of phase conductor to earth wire size on a 275 kV twin-conductor line is greater than on a 132 kV single-conductor line, and here, especially, I would have expected the earth wire to be struck with more certainty than any of the phase conductors. There is some doubt whether this actually happens.

Generally speaking, more lightning faults are experienced in areas of high earth resistance, even at 132 kV, where the impulse level of the insulation can be expected to be high enough to withstand the more numerous indirect surges resulting from line discharge in the vicinity of the line. Will the author comment on the influence of earth resistivity on the incidence of direct lightning discharge to lines of 132 kV and above? Clearly, under conditions of high tower-footing resistance, insulation failure will occur at lower stroke currents, but I wonder if soil resistivity can influence the bound charges. Would a localized area of high-resistance surface ground tend to give rise to the development of a higher quantity of bound charge which, on discharge, would produce abnormally high current?

Mr. J. W. Hopkins (*at Bristol*): The author shows the benefits achieved by the installation of a correctly spaced earth wire in the shielding of overhead lines against lightning. In the Area Boards, however, we are not in the fortunate position to benefit from this practice, as are our colleagues in the Division.

This is brought about by both economic considerations and the wayleave difficulties associated with steel-tower lines. Insulated wood-pole lines of B.S. 1320 type are used extensively at voltages from 6·6 to 33 kV. The Midlands Electricity Board are at present designing wood-pole lines with $0 \cdot 4\,\mathrm{in}^2$ aluminium conductors at 33 kV without provision for over-running earth wire, because of economic considerations. The prospect of ever building new steel-tower lines, or even wood-pole lines, with over-running earth wire is therefore remote.

The problem of protection against lightning has to be tackled differently as far as Area Boards are concerned. Emphasis has to be placed on absorbing lightning surges, as distinct from deflecting the stroke. At 11, 33 and 66 kV great attention has been given to the use of surge diverters, arcing horns and Petersen-coil earthing as a means of absorbing surges. In recent years Area Boards have introduced high-speed reclosers, pioneered by the Midlands Board, to protect against lightning surges on systems up to 11 kV. This practice is now being extended to cover all the rural overhead system by installation of high-speed-reclosing oil-filled circuit-breakers at primary substations.

This technique must eventually be extended to the 33 and 66 kV systems, particularly in the case of oil circuit-breakers controlling single transformer feeders, which are being used extensively to reinforce rural areas. High-speed tripping and reclosing of the controlling oil circuit-breaker will achieve a greater continuity of supply and will also prevent transient faults from developing into permanent faults by interruption before a power arc is maintained and equipment damaged.

Would the author agree, therefore, that the policy of Area Boards must be directed more towards protection by absorbing lightning surges, than towards the more expensive method of erecting overhead earth wires to prevent power lines being struck?

Dr. J. H. Gridley (*in reply*): Mr. Williams raises a most interesting and fundamental question: the distribution of leader-channel charge assumed in the paper was based on the best available evidence at the time of writing. A more intense concentration of charge at the head of the channel would cause equipotential lines of the associated electric field to be steeper in the vicinity of the channel, resulting in shielding failures on lines with a constructional angle of 45°. It might be noted that if the leader channel were regarded as well conducting and the charge distribution on it as settled by electrostatic forces only, the charge density at the head of the channel would indeed be larger than that assumed in the paper.

It is agreed that detailed studies of individual lightning faults on high-voltage lines would be most valuable, as suggested by Messrs. Williams and Campbell, but probably only supply authorities could carry out such surveys. Mr. Campbell's further remarks are not so readily accepted, however. It remains difficult to see how the relative sizes of phase and earth wires can influence the pre-strike phenomena when conducting corona envelopes have formed around both. When account is taken of the relatively low speed at which the leader channel descends it seems improbable that soil resistivity can influence the amount of bound charge, either on conductors or in the earth.

I agree with Mr. Hopkins that the most logical policy for Area Boards is that of minimizing the adverse effects of direct strokes, rather than seeking to shield distribution lines against such strokes. Indeed, unless heavy capital and maintenance costs can be contemplated, an attempt at shielding distribution lines might well result in greater numbers of outages.

DISCUSSION ON 'THE APPLICATION OF IRRADIATION IN INDUSTRY'*

Before the NORTHERN IRELAND CENTRE *at* BELFAST *8th November*, 1960, *and the* SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP *at* BIRMINGHAM *9th January*, 1961.

Dr. R. J. Magee (*at Belfast*): The greatest disadvantage of radiation is the lack of specificity. Even a simple solvent such as water under the action of radiation yields complex results. It is now established that H and OH radicals are produced, some hydrogen peroxide, and the radical HO_2 has been suggested. In the Chemistry Department of Queen's University recent work has been concerned with the irradiation, using γ-rays from cobalt 60, of organic compounds or metallo-organic complexes dissolved in non-aqueous solvents such as chloroform. By this means, results are more specific. A chlorine radical, or in the presence of oxygen a ClO_2 radical, is produced which attacks the solute. In some cases a new compound can be isolated. We have endeavoured with considerable success to turn systems of this type into chemical dosimeters for γ-radiation which have advantages over electronic instrumentation.

A field of study using radiation which has had great success is neutron-activation, or radioactivation analysis. By bombarding elements with neutrons, radio-elements of differing half-lives are produced which can be employed for the detection

* CROWLEY-MILLING, M. C.: Paper No. 3145, October, 1959 (see **107 A**, p. 111).

and determination of traces of impurities. An example is the determination of as little as 10^{-9} g of manganese in an aluminium alloy. Neutron irradiation produces from aluminium a radio-isotope of very short half-life, but from manganese a radio-isotope of much larger half-life is obtained. After decay of the aluminium activity, the activity of the manganese may be used to determine it. No other analytical method is as sensitive as the neutron-activation technique.

Mr. M. Taylor (*at Belfast*): Is there any evidence that, as a result of continued irradiation or bombardment, a strain of bacteria will evolve which is more resistant to the treatment? Furthermore is there any selectivity in the process of treatment? Are the bacteria causing, say, diphtheria any more or less vulnerable than those causing food poisoning? Can a virus be destroyed by this method of irradiation or electronic bombardment?

Mr. I. G. Edwards (*at Birmingham*): I take it that irradiation is allied to some form of radioactivity. I would like to know whether the molecular changes produced by irradiation are reasonably permanent and whether polythene permanently retains its irradiated characteristics or returns to its original molecular state after a certain time. Furthermore, what effect has irradiation on permittivity? I would like to know whether any experiments have been carried out on irradiating bitumen. Is it economical to purify cheap bitumen by this process and so produce a compound suitable for high-voltage use?

I wonder whether it is commercially possible to produce the extra-long-life car tyres mentioned in the paper, and what would the difference in price be compared with tyres produced by the normal process.

I would like to know what effect a power failure would have on an accelerator which is actually in operation.

Mr. M. C. Crowley-Milling (*in reply*): I agree with Dr. Magee that difficulties exist in interpreting the results of some irradiation experiments. The field of radio-activation analysis is certainly a very fruitful one, but is unfortunately outside the scope of the paper.

In reply to Mr. Taylor, I understand that investigations have been carried out to determine whether such a resistant strain could be produced. Although the repeated low-dose irradiation of a mixture of different strains of bacteria can lead to the selection of the more resistant strains, I know of no evidence that the resistance of a given strain can be increased by this method. Powell and Bridges* give some figures for the relative resistance of different organisms. Viruses can be inactivated by irradiation, but the doses required are higher than for bacteria.

In reply to Mr. Edwards, in most cases it is quite safe to handle the articles immediately after irradiation. Most of the molecular changes brought about by irradiation, including the cross-linking of polythene, are permanent. Other changes, such as discoloration of glass by the displacement of electrons in the crystal lattice, are temporary. The permittivity of a material is often increased by irradiation, but the effect is small for the dose needed to cross-link polythene, for example. I have not heard of any experiments with bitumen.

Car tyres are vulcanized in thick steel moulds to give the required shape and pattern. In the experiments quoted, a high proportion of the radiation was wasted in the mould. To make irradiation vulcanizing economically attractive, a new technique has to be developed.

In the case of a power failure, an accelerator would stop operating and there would be no radiation hazard. Protective relays prevent damage to the equipment, and even after a prolonged power failure the equipment can usually be in operation within an hour of the resumption of the supply.

* Powell, D. B., and Bridges, B. A.: *Research*, 1960, **13**, p. 151.

DISCUSSION ON 'THE APPLICATION OF LOW-PRESSURE RESINS TO SOME HIGH-VOLTAGE SWITCHGEAR DESIGNS'*

SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP AT BIRMINGHAM, 13TH FEBRUARY, 1961

Mr. I. G. Edwards: Can the authors say what is the comparative price of air-insulated and compound-insulated gear? Correct functioning of air-insulated switchgear depends on each of the component materials forming the insulation between live conductor and earth being stressed within safe limits. Breakdown of any one insulating layer would alter the stress distribution across the remainder and probably cause failure to earth. Such a breakdown might occur in the boundary layer between two insulating media, e.g. p.v.c. and resin.

Are the properties of the low-pressure resins described in the paper such that, under the mechanical forces arising from the use of air-insulated gear on circuits controlling fluctuating loads, e.g. rolling mills, welding, etc., no air voids are introduced into the boundary layers?

Apart from careful choice of the permittivities of the various insulants used, are any other methods of stress control adopted?

Mr. G. S. Buckingham: We are using epoxy resins in joint boxes for underground cables, one of the benefits being that we do not have to use a cast-iron box. The material is resistant to soil water and acids. We are using them in the form of liquids and the exothermic reaction is creating a temperature which may be having an effect on the p.v.c. cables being used.

Is there a critical size of casting which can be made with liquid resins before it cracks as it sets? There is a reference in the paper to resins cracking owing to their own exothermic reactions. What is the critical size of casting before it cracks under its own self-heating?

Mr. J. S. Woodhouse: Can the authors state how these castings are tested to ensure the elimination of all random cracks?

Mr. H. S. Lewis: It is mentioned in Section 3.2 that one method of producing voltage transformers is by packing the winding with silica flour and then impregnating. Are we to assume that the mould is still greased and, if so, what happens to the grease which is adsorbed by the silica flour?

Mr. H. F. Jones: The paper mentions only Araldite-type epoxy resins. Have the authors investigated the casting properties of the various competitive epoxy resins and compared their electrical properties for high-voltage applications?

The authors describe the use of an epoxy casting for the operating rod of a circuit-breaker. Was this reinforced by

* Manley, T. R., Rothwell, K., and Gray, W.: Paper No. 2835 S, February, 1959 (see 107 A, p. 213).

chopped fibres, and what is the maximum tensile strength obtainable?

Is any information available on coating of epoxy castings with resins to improve their resistance to surface flashover? Some work was done several years ago on the Continent: are the resins now available with improved surface electric strength?

Mr. E. Scarlett: In the commercial grades of silica filler available we find, among other things, traces of iron oxide, which constitute a potential source of electrical trouble. I do not know of any other material used as high-voltage insulation which is not subject to stringent standard specifications. Do the authors consider there is a case for the introduction of such a specification?

Referring to the red iron-oxide pigment used in the castings, it is true to say that the pigment is generally of no effect. However, if tests are made at high voltage under carbon-bearing oil it is easier to induce tracking in red-oxide-pigmented material than in castings containing no pigment. Is it therefore wise to use a metallic base pigment at all?

Would the authors please outline their method of assessing the corona resistance of this material?

Mr. J. Wainwright: Have the authors any information on how far the more unusual materials, produced in Switzerland and described in Reference 7, have been used in service and, if so, with what success? Are they still at the development stage or even the patent claim stage? There are some patents, for example, which suggest that resin-treated papers and fabrics can be rolled and cured under oil or even paraffin. Has this been tried in practice and, if so, with what results?

There is a reference to the performance of long-term higher-frequency tests with a view to accelerating the discharge erosion type of failure. As it is now at least three years since the paper was written and assuming a frequency of only 1 kc/s, these samples can have been subjected to the equivalent of 60 years at power frequency. Presumably there have been some failures during this time (assuming that the test stresses were higher than the 40 volts/mil fixed for service). Was it possible to follow the progress of the deterioration by periodic discharge tests or other means?

Some units must now have been in service for several years. Have any of these units been tested either at site or in the works to try to detect any changes in the state of the materials? Presumably the measurement of the discharge characteristics would be expected to be the most suitable method for this purpose.

Mr. J. S. Cliff: The authors have shown that these resins are very suitable for insulations having awkward shapes, and make possible many designs which could not be achieved with conventional forms of insulation: they are also very resistant to arcs. The circuit-breakers shown in Figs. 9 and 10 both have portions which are subjected to arcing, and also involve complicated shapes. Apparently cast resins are not used for these items, and it would be interesting to know whether the material has been tried, and what results were achieved.

Mr. E. V. Hardaker: What steps are taken to ensure that the finished product is free from voids? Is reliance placed upon efficiency of the manufacturing technique, or is a test made on the completed product?

Is there not a limitation, from both the manufacturing and security aspects, to the size and complexity of an epoxy casting? Where such a casting encloses or surrounds all three phases, any fault which may occur is likely to develop into a phase-to-phase fault, which usually takes a much longer time to clear.

I refer now to the use of epoxy castings in flameproof switch gear, where the principle of cooling the hot gases between the metal faces of a flange is adopted. It would appear from Fig. 11 that there is a metal surface on one side of the flange and an epoxy-resin surface on the other. Unless the drawing is in error, reliance is apparently placed on the epoxy-resin surface to cool the gas, which cooling cannot be so efficient as that provided by a metal surface.

Messrs. T. R. Manley, K. Rothwell and **W. Gray** (*in reply*): *To Mr. Edwards.*—It is a good general rule to design resin parts so that either any air-gaps close to the conductor are screened by electric stress shields or the stress on the air is so low that the ionization level is well above the working voltage.

At 11 kV a single stress shield is often used; this is connected to the earth terminal. This shield is usually made of wire mesh or a helical spring.

To Mr. Buckingham.—At the moment there appears to be no practical limit to the size of casting which can be made with liquid resins. For example, a recent cast was made where the filled resin mix was $\frac{3}{4}$ ton. Care must be taken, when curing large masses, to ensure that pouring and gellation is carried out at low temperature. The disadvantage of this is that the curing time is relatively long.

To Mr. Woodhouse.—In addition to extensive tests carried out on the prototype castings, each article is subject to a routine discharge test using a discharge bridge developed from that described by Arman and Starr* in 1936.

To Mr. Lewis.—Silicone grease is no longer used as a release agent on the mould but has been replaced by a silicone liquid which is baked to produce a hard surface finish. There is little danger, therefore, of the release agent being washed into the casting. However, release troubles have been experienced owing to the silica scratching the release agent from the mould surface.

To Mr. Jones.—There is a wide range of solid- and liquid-type resins available and these have been investigated. The solid resins similar to the Araldite B have almost identical properties, but there is no price advantage. The properties of various liquid-resin systems have been published elsewhere.†

The operating rod shown in the 500 MVA 11 kV air-break circuit-breaker was not reinforced, the working load being almost wholly compressive. In the 11 kV 250 MVA air-insulated oil-break unit, the operating rod was made from glass cloth and epoxy resin, the tensile strength being of the order of 38 000 lb/in^2.

Tests on various surface coatings are still in progress, but at present there is no indication that cast resin of any form is suitable for exposure outdoors where the surface of the resin is electrically stressed.

To Mr. Scarlett.—There is no doubt that the silica filler used in resin articles should be subject to stringent quality control by both chemical analysis and the measurement of the distribution of particle size. We have not observed that there is any difference between pigmented and unpigmented resins when under stress in carbonized oil. However, non-metallic pigments are now available and could be used.

To Mr. Wainwright.—Newer forms of insulants which are suitable for the manufacture of bent bushings are being produced both in Switzerland and in England on a production basis. The insulant referred to is known as Duresca B and contains no oil. Insulators up to 60 kV have been in service in Switzerland for at least three years, whereas those manufactured in England have been in service for only about six months.

The corona resistance of cast resin has been assessed by tests on samples and articles under both 50 c/s and 1–5 kc/s voltage duration.

* Arman, A. N., and Starr, A. T.: 'The Measurement of Discharges in Dielectrics', *Journal I.E.E.*, 1936, 79, p. 67.

† Rothwell, K., and Manley, T. R.: 'Recent Applications of Plastics in High Voltage Switchgear', *Transactions of the Plastics Institute*, August, 1961, 29, p. 110.

Articles which have been under 50 c/s voltage duration over the last 8 years have shown that, at stress levels of 40 V/mil with discharges greater than 400 pC, no measurable deterioration is obtained. Tests on samples stressed at 40 V/mil have an equivalent 50 c/s life of over 20 years. Current transformers energized at 6·6 kV and having discharge levels in excess of 500 pC have now been on test for a period equivalent to 50 years. Discharge tests during this period have shown no indication of progressive breakdown; impulse and 50 c/s breakdown tests carried out after 25- and 30-year test periods have shown no indication of incipient failure. Tests on current transformers which have been returned from site after six-years' service showed no signs of deterioration.

To Mr. Cliff.—The amount of solid carbon given off from epoxy resins when subject to power arcs makes the material unsuitable for arc-chute application.

To Mr. Hardaker.—Each article is subject to 50 c/s tests with a discharge bridge which ensures that it is free from voids.

We do not know of any manufacturing limit to the size of articles which can be made provided that the correct design is employed. With regard to Fig. 11, epoxy-resin systems are permissible in coal mines as insulation, and in a limited application as flameproof joints. The joints made with items cast in epoxy resin are treated in the same manner as other non-metallic joints, namely the flameproof-gap and flameproof-path dimensions are the same as those for metal-to-metal joints, but these are permitted only where the joints occur between two flameproof enclosures.

It is not permissible to use non-metallic material, even if it is in association with a metal face, to form a joint which communicates between a flameproof enclosure and the external atmosphere.

MONOGRAPHS PUBLISHED INDIVIDUALLY

Summaries are given below of monographs which have been published individually, price 2s. each (post free). Applications quoting the serial numbers as well as the authors' names, and accompanied by a remittance, should be addressed to the Secretary. For convenience, books of five vouchers, price 10s., can be supplied.

Mechanical Forces in Dielectrics. Monograph No. 475 M.

S. S. Hakim, Ph.D., B.Sc.

When a dielectric is subjected to an electric field, mechanical forces will be developed tending to deform the dielectric. A direct calculation of these forces is given using the polarization theory of dielectrics and it is shown that the result agrees with that derived from the Helmholtz energy method, the validity of which is proved. Only isotropic dielectrics are considered.

The Analysis of Thick-Cylinder Induction Machines. Monograph No. 477 U.

J. C. West, Ph.D., D.Sc., and D. E. Hesmondhalgh, M.Sc.

An analysis is given from fundamental principles of the performance of induction machines having smooth thick-cylinder rotors, both for polyphase and single-phase conditions. Flux and current distributions are obtained together with torque/speed characteristics and numerical values computed from the derived formulae. Experimental results obtained from a specially-constructed thick-walled rotor machine and from a single-sided linear machine are given for comparison.

Construction and Characteristics of a 340 MeV Electron Synchrotron Magnet. Monograph No. 478 M.

C. Ambasankaran, M.A., S. E. Barden, Ph.D., M.Sc.(Tech.), A. Finlay, B.Sc., B.E., Ph.D., J. B. Hansell, B.Sc., and F. R. Perry, M.Sc.(Tech.).

Following an outline of the original specification of the magnet, its construction is described in detail. An abridged description of the magnet power supply is given.

The characteristics of the magnet as revealed by comprehensive magnetic measurements are recorded, with a brief outline of the measuring techniques used.

The quantities measured include the betatron orbit radius, the azimuthal variations of the guiding field at injection and as acceleration proceeds, and the field exponent n and its variation with azimuth. Measurements of many of these quantities were taken over a wide range of magnet excitation, and they led to a choice of the quarter-cycle of the magnet waveform to be used for acceleration, and of the value to which the magnet excitation should be reduced for the initial attempt to produce a beam.

An attempt is made to explain qualitatively some rather obscure aspects of the magnet's behaviour at the commencement of its operating cycle.

An Analytical Method taking account of Saturation and Hysteresis for Evaluating the Iron Loss in Solid-Iron Cores Subjected to an Alternating Field. Monograph No. 485 U.

Prof. N. Kesavamurthy, M.A., B.E., M.Sc.Tech., and P. K. Rajagopalan, B.E., M.S., Ph.D.

An attempt is made to obtain an analytical solution for the field distribution inside solid magnetic cores subjected to an alternating magnetic field when the range of operation of the magnetizing force is limited to the first portion (up to the knee) of the B/H curve that can be approximated to the form $B = \mu(H - \epsilon H^3)$, ϵ being small. As a first stage, an analytical method is developed for the solution of the partial differential equation of the form

$$\frac{\partial^2 H}{\partial x^2} = \frac{\mu}{\rho}\frac{\partial}{\partial t}(H - \epsilon H^3)$$

H being a function of x and t.

Based on this method expressions for the field distribution, eddy-current loss and overall power factor are deduced. Furthermore, the above analysis is modified to take account of the presence of hysteresis. It is claimed that the method gives a clear picture of the saturation phenomenon and offers an explanation for the increases in loss and power factor that accompany saturation. The analysis is applied to the specific case of a mild-steel toroid and verified against the test results.

A Locus Diagram to Determine the Complete Starting Performance of a 3-Phase Induction Motor Connected to a Single-Phase Supply. Monograph No. 486 U.

A. R. Daniels, M.Sc., and B. R. Pelly.

A graphical solution, which gives the sequence voltages, starting-torque ratio, line current, the voltage across the capacitor and the corresponding values of a dimensionless admittance ratio for a 3-phase induction motor at standstill and connected to a single-phase voltage, is derived. Several optimum conditions, in particular an exact admittance ratio for minimum unbalance, are obtained from the locus diagram. In all cases it is shown that the admittance ratio obtained is independent of the applied voltage and the locus diagram is therefore applicable to machines of any rating.

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ABBREVIATIONS

(P)—Address, lecture or paper.
(D)—Discussion.
(A)—Abstract of paper or address.

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PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, DECEMBER 1961

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